AD-A091 508 NAVAL TRAINING EQUIPMENT CENTER ORLANDO FL F/G 5/8

SURVEY OF CIG DATA BASE GENERATION FROM IMAGERY.(U)

SEP 80 D R BREGLIA

UNCLASSIFIED NAVTRAEQUIPC-IH-318 NL

1 of 1

AD A091508

END

DATE FILMED

12 80

DTIC

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE — READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER NAVTRAEQUIPCEN IH-318	2. GOVT ACCESSION NO. AD-A092	3. RECIPIENT'S CATALOG NUMBER 508
4. TITLE (and Subtitle) (6) Survey of CIG Data Base Generation From Imagery		5. TYPE OF REPORT & PERIOD COVERED Interim Report for Period October 1978-December 1979
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) Denis R. Breglia (12) 83		8. CONTRACT OR GRANT NUMBER(s) (11) Sep 80
9. PERFORMING ORGANIZATION NAME AND ADDRESS Advanced Simulation Concepts Laboratory Code N-73 Naval Training Equipment Center Orlando, FL 32813		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NAVTRAEQUIPCEN Task No. 8734
11. CONTROLLING OFFICE NAME AND ADDRESS (14) NAVTRAEQUIPC-IH-318		12. REPORT DATE September 1980
		13. NUMBER OF PAGES 78
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) (9) Interim technical rept. 1 Oct 78-31 Dec 79		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Computer Image Generation (CIG)
Visual Simulation, Stereophotogrammetry
Digital Image Processing
Geometric Modeling

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The generation of an environment model for a Computer Image Generation (CIG) system is currently a labor intensive, expensive effort. This report reviews an extensive amount of literature covering the topics of scene complexity requirements in a visual simulation system, the structure of the data required by existing three-dimensional graphic algorithms, the application of photogrammetric and digital image processing techniques to assist the modeler, and recommendations for a modeling facility.

3904 2 slb

TABLE OF CONTENTS

ILLUSTRATIONS

SECTION I

INTRODUCTION

VISUAL SIMULATION

The function of a visual simulation system in a training device is to present a view of a simulated real world environment to a weapon system operator trainee. Visual simulation technology can be categorized into two broad technology areas; image generators and displays. An image generator accepts information regarding the viewpoint and viewing direction of the observer and creates the simulated real world imagery in the format suitable for the display system. The display system then presents the view to the observer. Image generators contain a physical or mathematical model of a real world environment from which the required view or scene information is obtained. An example of an image generator which uses a physical model is a system which employs a television camera and a three-dimensional scaled terrain model board for simulating a pilot's view as he flies over the terrain. A computer image generator (CIG), on the other hand, processes a mathematical model of the visual environment to produce the required scene information. Prior to the advent of CIG technology, the camera-modelboard type of system dominated image generator technology. The reasons for the current trend toward CIG technology have been summarized by Wekwerth[1]. The areas of comparison included; depth of focus (limited with camera at low altitudes), stability (degradation of electro/mechanical components with camera system), gaming area (modelboard size and scale restricted), flexibility (changing environments in a CIG system is easier than changing a modelboard), and power consumption (150KW for modelboard vs. 15KW for CIG) among a dozen other reasons. Other investigators (O'Connor[2], Monroe[3], Thorpe[4]) have pointed out the advantages of CIG systems in terms of training effectiveness.

---

[1] Wekwerth, M., "The Lufthansa Day/Night Computer Generated Visual System", in AGARD Conference Proc. No. 249 (ADA063850), pp. 12-1, 12-6, April 1978.

[2] O'Connor, F; Shinn, J.; and Bunker, W., "Prospects, Problems, and Performance: A Case Study of the First Pilot Trainer Using CGI Visuals", in Proc. of Sixth NTEC/Industry Conference, pp. 55-83, November 1973.

[3] Monroe, E., "Air to Surface Full Mission Simulation by the ASUPT System", in Proc. of 9th NTEC/Industry Conference, pp. 41-48, November 1976.

[4] Thorpe, J.; Varney, N.; McFadden, R.; LeMaster, W.; and Short, L., "Training Effectiveness of Three Types of Visual Systems For KC-135 Flight Simulators", Air Force Human Resources Laboratory, Flying Training Division Report AFHRL-TR-78-16, June 1978.

COMPUTER IMAGE GENERATION SYSTEMS

The real-time CIG systems currently employed in visual simulation systems resulted as an outgrowth of the field of computer graphics. Newman[5] provides an excellent source for review of the mathematics and algorithms utilized in computer graphics. Non-real-time computer graphics research is primarily directed toward creating more realistic computer generated scenes (Crow[6], Csuri[7]) with little regard to the amount of computation time and hardware required. Real-time CIG research is primarily directed toward the same end within the hardware and time constraints of a real-time system. (A real-time CIG creates a complete new scene every 1/30 second with a pipeline computation time of less than 1/10 second). Morland[8] describes the design and capabilities of the CIG system developed for the NAVTRAEQUIPCEN Visual Technology Research System, developed by General Electric. Woomer[9] describes an implementation of a calligraphic CIG system developed by McDonnell Douglas. Schumacker[10] compares calligraphic CIG to Raster CIG. Potential improvements to the state of the art of real time CIG systems are described by Bunker[11], Marconi[12], and Swallow[13].

---

[5] Newman, W. and Sproull, R., "Principles of Interactive Computer Graphics", 2nd Edition, McGraw-Hill Book Company, 1979.

[6] Crow, F., "Shaded Computer Graphics in the Entertainment Industry", in Tutorial on Computer Graphics, IEEE Catalog No. EHO-147-9, 1979.

[7] Csuri, C., "Computer Graphics and Art", in Tutorial on Computer Graphics, IEEE Catalog No. EHO-147-9, pp. 421-433, 1979.

[8] Morland, D., "System Description - Aviation Wide-Angle Visual System (AWAVS) Computer Image Generator (CIG) Visual System", Technical Report NAVTRAEQUIPCEN 76-C-0048-1, Naval Training Equipment Center, Orlando, Florida, February 1979.

[9] Woomer, C. and Williams, R., "Environmental Requirements for Simulated Helicopter/VTOL Operations From Small Ships and Carriers", in AGARD Conf. Proc. No. 249, Piloted Aircraft Environment Simulation Technologies, ADA063850, October 1978.

[10] Schumacker, R. and Rougelot, R., "Image Quality: A Comparison of Night/Dusk and Day/Night CGI Systems", in Proceedings of the 1977 Image Conference held at Williams AFB, Arizona, 17-18 May 1977, pp. 243-255.

[11] Bunker, W., "Computer Image Generation Imagery Improvement: Circles, Contours, and Texture", Technical Report AFHRL-TR-77-66, Advanced Systems Division, Air Force Human Resources Laboratory, Wright-Patterson Air Force Base, Ohio, September 1977.

[12] Marconi Radar Systems Limited, Product Brochure, "A Picture Generator for Flight Simulators".

[13] Swallow, R., "Computrol Computer Generated Day/Dusk/Night Image Display", in Proceedings of 11th NTEC/Industry Conference, pp. 321-331, November 1978.

CIG technology is rapidly growing and the capability to process a complex environment in real-time is a reality. However, the process to create the complex environment model is currently labor intensive and expensive. The purpose of this report is to propose techniques to make the environmental data base creation process more efficient.

DATA BASE CONTENT

The basic information stored in the environmental model or data base is geometry and appearance. The specific requirements as to the size of the gaming area, the minimum size of details in the gaming area, the number of details in a given scene, and the required fidelity to the real world is strongly influenced by the tasks required for the specific mission being trained. In many cases the requirements are unknown. Often there is a need for the data base to represent actual real world areas rather than generic areas. For example, if the task is to navigate a ship in Norfolk Harbor the data base should represent Norfolk Harbor. Many training tasks require that the weapon system operator use a variety of sensor systems. In these cases the data bases must correlate. For example, the radar data base should have features located in the same geographic position as the visual data base. Hoog[14,15] and Basinger[16] discuss the general requirements for a data base and make a good case for the use of information which represents the real world (DMA[17]) as a framework from which CIG data bases can be built.

DATA BASE CONSTRUCTION

The structure or form in which the data is organized is a function of the CIG processing technique. Sutherland[18] classifies the various processing

---

[14]Hoog, T.; Dahlberg, R.; and Robinson, R., "Project 1183: An Evaluation of Digital Radar Landmass Simulation", in Proceedings of NTEC/Industry Conference NAVTRAEQUIPCEN, IH-240, pp. 54-79, November 1974.

[15]Hoog, T. and Stengel, J., "Computer Image Generation Using the Defense Mapping Agency Digital Data Base", in Proc. of the 1977 Image Conference at Williams Air Force Base, pp. 203-218, May 1977.

[16]Basinger, J. and Ingle, S., "Data Base Requirements for Full Mission Simulation" in Proceedings of the 1977 Image Conference, Air Force, Human Resources Laboratory, Flying Training Division, Williams AFB, Arizona, pp. 25-33, May 1977.

[17]Defense Mapping Agency, "Product Specifications for Digital Landmass System (DLMS) Data Base, PS/ICD-E-F-G/100, July 1977.

[18]Sutherland, I.; Sproull, R.; and Schumacker, R., "Characterization of Ten Hidden-Surface Algorithms", Computing Surveys, Vol. 6, No. 1, pp. 1-55, March 1974.

algorithms which utilize data bases in which the information is stored as planar polygons. In current, real-time CIG systems polygon models are the basic data structure. Monroe[19] describes the techniques utilized in the construction of a polygon data base. Kotas[20] describes the polygon data base construction facility at NAVTRAEQUIPCEN.

REPORT SUMMARY

This report is primarily the result of a literature search and is not meant to be an in-depth discussion of the subjects covered. The prime purpose was to provide an overview of the problems involved in CIG data base construction and discuss the technologies which are pertinent to the automation of data base development. In Section II of this report a description of modeling criteria in terms of scene detail is proposed. Section III describes the various data base structures used in computer graphics with the understanding that real time CIG systems currently use polygon representations but future CIG systems might require different data base structures if only to make the modeling task more efficient. Section IV discusses stereophotogrammetric and digital image processing techniques for extracting CIG data base information from photographs. Section V describes the components of a modeling system in terms of the hardware necessary to implement stereophotogrammetric and digital image processing of imagery for CIG data base development.

---

[19]Monroe, E., "Environmental Data Base Development Process for the ASUPT CIG System", Air Force Human Resources Laboratory, Technical Report AFHRL-TR-75-24, August 1975.

[20]Kotas, J. and Booker J., "The AWAVS Data Base Facility - A Comprehensive Preparation Package", in Proc. of 11th NTEC/Industry Conference, pp. 49-62, November 1978.

SECTION II

SCENE DETAIL REQUIREMENTS

INTRODUCTION

In this Section an attempt is made to identify and quantify the information which is operated on by the CIG system to produce a simulated visual environment. This information includes geometric information such as size, shape, and location as well as the less easily defined modes of appearance such as brightness, hue, saturation (these three can also be called spectral luminance), transparency, and glossiness. The scene illumination also affects the appearance. Illumination has spectral properties and objects in the scene have reflectance properties which are a function of color and direction (OSA[21]).

This Section discusses; the difference between seeing and perceiving, the capabilities of the eye, scene parameters affecting the performance of certain visual tasks, and recommendations for scene detail requirements.

SEEING VERSUS PERCEIVING

The purpose of a weapon system trainer is to provide an environment which will teach and exercise an operator in those skills required in the performance of his mission tasks in the actual weapon system. Since an operator's performance is based on his perception of his environment, the simulated environment *should be perceptually similar to the real world environment.* The visual simulation system in a weapon system trainer provides a visual environment to the operator which should be perceptually similar to the real world visual environment. In a CIG visual simulation system the operator's perception of his environment can be considered; to originate in the data base, to proceed through the image generation and the display system, to be seen by the observer's eyes, and finally to be operated on by the observer's perception process (involving his memory, emotional state, and concentration) to yield his perception. The information rate of the eye-brain perception process has been estimated at 5×10^3 bits/second (Sagan[22]). If this process could be accurately determined any visual environment could be perceptually replicated at this relatively low information data rate. Unfortunately, the perception process is difficult to analyze and quantify. Consequently, a visual simulation system attempts to replicate what the eye can see in the real world with sufficient similarity such that the perception is functionally identical to the observer's perception in the real world as measured by training transfer. There is no conclusive research as to the required degree of realism or fidelity necessary to train. In order to be

---

[21] Optical Society of America, "The Science of Color", Optical Society of America, Washington, D.C., 1963.

[22] Sagan, C., "The Dragons of Eden", Ballantine Books, New York, 1977.

confident that positive transfer of training is occurring two general rules are usually followed (Hamilton[23]); maximize the similarity between the simulated and operational environments, and provide adequate experience with the task.

Another driving force behind emphasizing perceptual fidelity as opposed to realism is the high cost of realism. Replication of all sensible attributes of the real world is potentially possible but also very expensive.

Although the concept of perceptual fidelity has been voiced before (Wood[24]), the design and specification of visual simulation systems will continue to be based on physical fidelity to the real world until those trade-offs on realism required for specific training transfer have been quantitatively identified. For example, Welch[25] states that good texture and parallax cues are sufficient for piloting training in the nap-of-the-earth (NOE) mission but the navigation training requires a much more complex set of topographic, hydrographic, and botanical cues. The visual cues required for the simulation of the full NOE mission almost defy analysis. Gibson[26] points out that the visual stimulus need only be a correlate of the real world property, not a copy of it, in order for the perception to be the same. Bunker[27] describes an example in which parallel converging lines serve the same function as a texture gradient to produce a perception of depth in a visual simulation.

In this Section the performance parameters of the eye will be reviewed as well as some perceptual parameters which have been measured for specific visual tasks. It is recommended that data base content be based on perceptual fidelity as a goal. However, it must be kept in mind that many tasks have not been studied sufficiently to determine just what scene qualities are necessary to produce perceptual fidelity. In cases such as NOE navigation it may be necessary to have all of the visual fidelity of the real world simply because the trade-offs are unknown.

---

[23] Hamilton, H., "Feasibility Study for Simulation of an Airport Tower Control Environment", ADA051174, February 1978.

[24] Wood, M., "The Fidelity Issue in Visual Simulation", in Proc. of the 1977 Image Conference, Williams AFB, pp. 291-295, May 1977.

[25] Welch, B., "Recent Advances in Television Visual Systems", in AGARD Conference Proceedings #249, ADA063850, pp. 13-1, 13-7, April 1978.

[26] Gibson, J., "The Perception of the Visual World", Houghton-Mifflin Company, Boston, 1950.

[27] Bunker, W., "Training Effectiveness Versus Simulation Realism", SPIE, Vol. 162, Visual Simulation and Image Realism, pp. 76-82, August 1978.

VISUAL CAPABILITIES

The performance capability of the eye has been extensively studied and reviewed many times and reported elsewhere (Booth[28], Carel[29], Farrell[30]). In order to demonstrate the magnitude of the problem in trying to replicate the visual environment a brief description of some of the capabilities of the eye are summarized in the following paragraphs.

Acuity. Acuity is defined as the reciprocal of the angle, measured in arc minutes, of the smallest detail which can be resolved. Acuity varies with luminance, color, contrast, and position in the field of view (LeGrand[31]). For high contrast targets, viewed on-axis, the minimum separable acuity at 10 FTL (Foot Lamberts) is 2.0. This corresponds to a bar target with an angular frequency of one line pair per arc minute. Vernier acuity, which is the ability to see a misalignment in a line, and stereo acuity, which is the ability to see the angular disparity due to the eye separation distance, are both approximately 0.04 arc minutes. The minimum perceptible angular subtense of a non luminous detail is approximately 0.007 arc minutes.

The above acuity thresholds can be combined with the closest approach distance to be simulated to give an idea of the size of details which the eye is capable of seeing in the real world. The minimum perceptible acuity criteria allows power lines to be seen against a uniform sky. Under ideal conditions a power line only a half inch thick can be seen at a range of three miles. At a range of 5 meters a spider web strand only 10 microns thick can be seen. Vernier acuity thresholds indicate that breaks in edges due to misalignment of two juxtaposed displays can be seen with misalignments as small as 34 microns on a screen located 3 meters from the observer. Stereo acuity becomes important in a stereo display system in which separate displays are computed for the viewpoint of each eye. This has implications on the precision with which a viewpoint is located for scene computation. For example, to replicate the stereo capability of an observer viewing an object located 5 meters away, the viewpoint positions must be precise to a linear dimension of 34 microns in real world coordinates.

---

[28] Booth, J. and Farrell, R., "Overview of Human Engineering Considerations for Electro-Optical Displays", SPIE, Vol. 199, pp. 78-108, August 1979.

[29] Carel, W.; Herman, J.; and Olzak, L., "Design Criteria for Imaging Sensor Displays", ADA055411, May 1978.

[30] Farrell, R. and Booth, J., "Design Handbook for Imagery Interpretation Equipment", Boeing Aerospace Company, Seattle, Washington, December 1975.

[31] LeGrand, Y., "Form and Space Vision", Indiana University Press, Bloomington, 1967.

The minimum separable acuity threshold is the one most often used as the ultimate goal in a visual display system. As evidenced by the above discussions a data base minimum detail dimension criteria based on a minimum separable acuity threshold would not replicate the potentially visible environment. The minimum separable threshold applies to a large percentage of, but not all, visual tasks. Minimum separable acuity is that visual performance parameter which is used to read the letters in an eye chart. For example, 20/20 vision as measured on a Snellen chart corresponds to a separable acuity of 1.0 or a resolution of 2 arc minutes/line pair. A person with 20/20 vision is capable of reading letters whose lines or gaps subtend 1 arc minute or approximately 1/16 inch at 20 feet.

Luminance. The range of light levels to which the eye can respond extends from 10^{-6} FTL to 10^{4} FTL or approximately 10 orders of magnitude. However, at any one time the eye is limited to approximately two orders of magnitude of luminance discrimination due to the brightness - adaption mechanism of the eye (Cornsweet[32]). Consider a sunlit environment. The adaptation level adjusts to its maximum range. All luminances above 10^{4} FTL are seen as white; all luminances below 10^{2} FTL are seen as black. Now consider a dark interior or an overcast night. The eye adapts to its minimum range. All luminances below 10^{-6} FTL are black while all above 10^{-4} FTL are white (assuming the eye is not allowed to adapt to luminances higher than 10^{-4} FTL). Since display systems typically are restricted to a dynamic range of 100:1, or less, CIG systems have generally computed display information over this same range. If, however, visual environment simulations are to include the effects of adaptation to different luminance levels, while maintaining the dynamic range, then the computation of pixel luminance in the display should be carried out over the entire range of luminances consistent with the dynamic scenario. For example, consider a battlefield scenario on a cloudy, moonless night. The display system has a highlight brightness of 10 FTL and a dark level of 0.1 FTL. The simulated scene has absolute luminance levels extending from 10^{-6} to 10^{-4} FTL which are effectively simulated by the display which calls 10^{-4} FTL white and displays at 10 FTL while 10^{-6} FTL is called black and displayed as 0.1 FTL. (For illustration, contrast effects have been ignored). A "white" object is seen against a "black" treeline. Now a parachute flare ignites behind the treeline with the "white" object in shadow. In the real world the eye would adapt to the new luminance level (call it 10^{4} FTL) and the previously "white" object would appear black while the tops of the trees which were black are now illuminated by the flare and appear white. If the dynamic range of luminance computation is restricted to two orders of magnitude this situation could not be effectively simulated. The same reasoning applies to less extreme examples such as a pop-up maneuver from a small clearing in a dense forest or the effect of headlights or search lights. Note that the display dynamic range is not at issue, just the computational luminance range.

---

[32]Cornsweet, T., "Visual Perception", Academic Press, New York, 1970.

Contrast. The perception of luminance differences is a function of color and luminance level. The problem of modeling observable color differences is complex and beyond the scope of this report. The interested reader is referred to MacAdam[33] and Hunt[34]. Contrast sensitivities to luminance level differences can be measured by observing a uniformly lit screen of luminance B. A sharp edged area within the screen has additional luminance of ΔB. The luminance ΔB is increased from zero until it is just noticeable. The just noticeable difference ΔB is measured as a function of B. The quantity $\Delta B/B$ is called the Weber Ratio (Gonzalez[35]). This quantity for typical display luminance ranges is approximately 10% at 0.1 FTL decreasing to 2% at 1 FTL and remaining fairly constant at 2% to 10 FTL.

In terms of absolute luminance levels the Weber fraction increases to 10 at luminance levels of 10^{-3} FTL or less allowing the discrimination of only two or three gray levels. To more accurately simulate the situation described above, the "white" object might be assigned a display luminance value of 5.1 FTL while the black trees are displayed at 5 FTL.

Note that luminance difference thresholds are a function of luminance level. Since CIG systems treat luminances in a linear, digitized fashion for computational purposes the computations are carried out with fixed luminance differences. If the appearance of the resultant display is to replicate the eye's capability then the fixed luminance difference should be equal to the smallest luminance difference observable. This would lead to luminance steps of 0.01 FTL or 1000 steps to span the display range of 0.1 to 10.0 FTL. In practice luminance computations carried to 8 bit accuracy (256 steps) are usually acceptable. If the entire dynamic range of eye perceivable luminance levels is to be simulated (as discussed above) then the smallest perceptible luminance level is approximately 10^{-4} FTL requiring 10^8 steps and 20 bit accuracy.

In a color display formed by the combination of three separately modulated colors the above analysis is applicable with some modification. A predominantly red color can be distinguished from another predominantly red color at the same luminance level with a change in the red component of the order of 2%. However, a predominantly blue color needs a larger relative change in the red component to be distinguished.

---

[33] MacAdam, D., "Visual Sensitivities to Color Differences in Daylight", Journal of the Optical Society of America, Vol. 32, No. 5, pp. 247-274, May 1942.

[34] Hunt, R., "The Reproduction of Colour", Fountain Press, England, 1975.

[35] Gonzalez, R. and Wintz, P., "Digital Image Processing", Addison-Wesley Publishing Co., Reading, Massachusetts, 1977.

VISUAL TASK PERFORMANCE

The problem of developing a visual simulation system which provides imagery indistinguishable from the real world is not a valid goal for training. The goal, as stated previously, is to provide an environment in which visual skills can be learned. In the following paragraphs some data on the visual information required to perform certain visual tasks will be described.

Shape Recognition. LeGrand[36] gives criteria for recognizing geometric forms as 3 arc minutes for the length of the sides of a triangle; 4 arc minutes for the sides of a square; 4 arc minutes for the diameter of a circle; and a 1% difference in axis length for distinguishing a circle from an ellipse.

Color. The requirement for color versus monochrome displays in a visual simulation system has not been experimentally verified. Target detection experiments (Wagner[37]) indicate that color is better but not significantly. For visual search and identification tasks, Christ[38] has found that there is no particular advantage or disadvantage as measured by task performance for many tasks. However, he found that for some tasks color could be very effective under certain conditions. Ali[39] describes a color-based computer analysis of aerial photographs in which color not only provides an identifying feature with which a particular object can be recognized by the machine, but also provides a basis for the initial separation of the individual objects in the perception of the scene.

Although color has not yet been demonstrated to be necessary in visual simulation for training it is usually one of the items specified as desirable

---

[36] LeGrand, Y., "Form and Space Vision", Indiana University Press, Bloomington, 1967.

[37] Wagner, D., "Target Detection With Color Versus Black and White Television", Report TP5731, Naval Weapons Center, China Lake, CA, April 1975.

[38] Christ, R., "Four Years of Color Research for Visual Displays", in Proc. of Human Factors Society - 21st Annual Meeting, pp. 319-321, October 1977.

[39] Ali, M. et al., "Color-Based Computer Analysis of Aerial Photographs", Computer Graphics and Image Processing, Vol. 9, pp. 282-293, 1979.

by the trainees (Rivers[40], Chase[41]). McGrath[42] provides a rationale for color simulation based on pilot training objectives and various mission tasks in terrain flight.

Gray Levels. Mezrich[43] has developed a vision model to compute the number of just noticeable differences in display perception. He states that 6 bits suffice for a 10 FTL display. Another interesting parameter described in his report is that the contrast sensitivity peaks at 3 cycles/degree as seen by the observer. He also found that the power spectrum of natural scenes could generally be described by 5 bits of luminance and that the perceived information capacity of a color display is more than a monochrome for the same bandwidth.

Texture. Richards[44] has proposed that texture perception is analogous to color perception. The eye's response to colors can be explained by assuming the presence of three detectors in the retina, each one having different spectral response. Richards proposes and finds experimental evidence that texture perception can be explained by the presence of texture sensors in the retina. He has found that the texture "primaries" are approximately 1, 3, 6, and 11 cycles/degree. Therefore, any texture can be simulated by forming its texture metamer from a composition of these spatial frequencies. Since the texture primaries are defined in terms of subtended visual angle, the synthesis of a given texture is a function of range and aspect angle of the textured surface.

Flight Training. Stark[45] describes a methodology for selecting the visual information for CIG representation. For example, air to air training tasks require only a checkerboard simulation of the ground to enable the trainee to obtain cues to his altitude, altitude rate, and ground speed and highly

---

[40] Rivers, H. and VanArsdall, R., "Simulator Comparative Evaluation", in Proc. of 10th NTEC/Industry Conference, pp. 37-42, November 1977.

[41] Chase, W., "Effect of Color on Pilot Performance and Transfer Functions Using a Full-Spectrum, Calligraphic, Color Display System" in Proceedings of AIAA Vision Simulation and Motion Conference, April 1976.

[42] McGrath, J., "The Use of Wide-Angle Cinematic Simulators in Pilot Training", Technical Report NAVTRAEQUIPCEN 70-C-0306-1, March 1973.

[43] Mezrich, J.; Carlson, C.; and Cohen, R., "Image Descriptors for Display", Office of Naval Research Report ONR-CR213-120-3, February 1977.

[44] Richards, W., "Experiments in Texture Perception", ADA059630, January 1978.

[45] Stark, E.; Bennett, W.; and Borst, G., "Designing DIG Images for Systematic Instruction", in Proc. of 10th NTEC/Industry Conference, pp. 147-155, November 1977.

detailed imagery of the target aircraft to make effective judgments of range and attitude. Basinger[46] describes the qualitative attributes of a full mission simulation. Ritchie[47] emphasizes that perception is strongly subjective and highly task dependent in developing design criteria for CIG systems. These reports point out the need for research to develop perceptual criteria based on training effectiveness.

Rivers[48] describes an experiment in which Tactical Air Command (TAC) pilots performed subjective evaluations of existing flight simulators. Their subjective opinion was that current systems are inadequate for air-to-surface tasks. They voiced a need for: multiple moving targets; a runway; controlled ceiling and visibility; adequate gaming area; realistic color; sufficient scene content and detail to determine airspeed, altitude, and area orientation; visual grayout/blackout; sun image; field of view equivalent to the aircraft FOV; and weapons effects.

Kraft[49] and Chase[50] evaluated pilot acceptance, pilot performance, and training transfer using CIG imagery. Kraft found that CIG provides acceptable crew training for the approach and landing task in commercial aircraft. Chase found different levels of pilot performance and acceptability with different colors in a calligraphic display.

Kraft[51] describes the results of a study to develop criteria for visual system for flight crew training in air transports. He concludes that the visual simulation criteria are primarily driven by equipment limitations. His recommendations are a minimum of 6 FTL display luminance (performance drops off below 6 FTL) and display resolution of 3 arc minutes/pixel for daylight scenes.

---

[46] Basinger, J. and Ingle, S., "Data Base Requirements for Full Mission Simulation" in Proceedings of the 1977 Image Conference, Air Force, Human Resources Laboratory, Flying Training Division, Williams AFB, Arizona, pp. 25-33, May 1977.

[47] Richie, M., "Object, Illusion, and Frame of Reference as Design Criteria for Computer-Generated Displays", SPIE, Vol. 162, Visual Simulation and Image Realism, pp. 8-10, August 1978.

[48] Rivers, H. and VanArsdall, R., "Simulator Comparative Evaluation", in Proc. of 10th NTEC/Industry Conference, pp. 37-42, November 1977.

[49] Kraft, C.; Elworth, C.; Anderson, C.; and Allsopp, W., "Pilot Acceptance and Performance Evaluation of Visual Simulation", in Proc. of 9th NTEC/Industry Conference, pp. 235-249, November 1976.

[50] Chase, W., "Effect of Color on Pilot Performance and Transfer Functions Using a Full-Spectrum, Calligraphic, Color Display System" in Proceedings of AIAA Vision Simulation and Motion Conference, April 1976.

[51] Kraft, C. and Shaffer, L., "Visual Criteria for Out of the Cockpit Visual Scenes", in AGARD Conference Proceedings No. 249, ADA063830, pp. 3-1, 3-18, April 1978.

Terrain Flight. Ozkaptan[52] describes the visual requirements for nap-of-the-earth flight simulation as: resolution of 3 arc minutes/pixel; luminance of 50-100 FTL; field of view of 40° X 120°; full color; simulated range to 20 miles. Key[53] describes the visual requirements for an Army Rotorcraft Research Simulator. He states that for an obstacle avoidance task in NOE flight a field of view of at least 60° X 180° is required. Resolution for this proposed research simulator is specified as 3 arc minutes/pixel or better. Key states that objects such as targets can be made artificially large in this simulator since combat simulation for training is not the goal. Sanders[54] has experimentally determined that the task of navigation during terrain flight consumes 92% of the navigator's time. He has described this task as primarily a correlation task in which the navigator first searches and then pattern matches. The navigator correlates his view of the terrain with his map or photographs, taking into account seasonal changes, visibility, illumination, day/night differences, and changes in fields and roads since his reference information was obtained.

Target Acquisition. This visual task has apparently generated the greatest amount of perception data available. Many experimental results under a variety of conditions are described by Farrell[55]. The subject views a displayed scene containing a target and background. His task it to acquire the target. His performance is usually measured as a function of display parameters such as resolution, contrast, field of view and display time. The performance criteria is usually defined in terms of detection (something is present in field); orientation (where it is in field); recognition (recognizing that the object belongs to a class); and identification (identification of type within class). Biberman[56] gives the general quantitative resolution requirements in terms of the number of line pairs subtended by the minimum critical object dimension

---

[52] Ozkaptan, H., "Critical Visual Requirements for Nap of the Earth (NOE) Flight Research", in Proc. 8th NTEC/Industry Conference, pp. 53-65, November 1975.

[53] Key, D.; Odneal, B.; and Sinacori, J., "Mission Environment Simulation for Army Rotorcraft Development - Requirements and Capabilities", in AGARD Conference, Proc. #249, (ADA063850), pp. 4-1, 4-17, April 1978.

[54] Sanders, M.; Simmons, R.; Hofmann, M.; and DeBonis, J., "Visual Workload of the Co-Pilot/Navigator During Terrain Flight", Proc. of the Human Factors Society 21st Annual Meeting, pp. 262-266, October 1977.

[55] Farrell, R. and Booth, J., "Design Handbook for Imagery Interpretation Equipment", Boeing Aerospace Company, Seattle, Washington, December 1975.

[56] Biberman, L. (Editor), "Perception of Displayed Information", Plenum Press, New York, 1973.

as: Detection = 1.0; Orientation = 1.4; Recognition = 4; and Identification = 6.4. Booth[57] gives similar values with the caveats that the subtended visual angle must exceed 12 arc minutes and that the results are highly dependent on the task and the background. Scott[58] measured identification only and scored correct percentage of responses. His subjects scored 20% correct at 1.5 line pairs and 90% at 7 line pairs per minimum vehicle dimension. Scanlan[59] measured time to detect as a function of background complexity. He found that detection time for a high-complexity background was 24 times that of a uniform background. Gaven[60] measured identification as a function of line pairs per vehicle and the number of gray levels. He found that the number of quantized gray levels is inversely proportional to the number of lines per vehicle for a given level of performance. Craig[61] found that, for a given number of lines per vehicle, performance improved as the field of view increased to approximately 10° then leveled off. The target size was a minimum of 30 arc minutes.

The quantification of background complexity in terms of perception and cognition has been attempted by Ciavarelli[62] and Hall[63]. Until such a target-background complexity metric has been defined and tested relative to performance of specific visual tasks the specification and evaluation of background complexity will continue to be subjective.

---

[57] Booth, J. and Farrell, R., "Overview of Human Engineering Considerations for Electro-Optical Displays", SPIE, Vol. 199, pp. 78-108, August 1979.

[58] Scott, F.; Hollanda, P.; and Harabedian, A., "The Informative Value of Sampled Images as a Function of the Number of Scans Per Scene Object", Photographic Science and Engineering, Vol. 14, No. 1, pp. 21-27, January 1970.

[59] Scanlan, L., "Target Acquisition in Realistic Terrain", in Proc. of the Human Factors Society - 21st Annual Meeting, pp. 249-253, October 1977.

[60] Gaven, J.; Tavitian, J.; and Harabedian, A., "The Informative Value of Sampled Images as a Function of the Number of Gray Levels Used in Encoding the Images", Photographic Science and Engineering, Vol. 14, pp. 168, 1970.

[61] Craig, G., "Vehicle Detection on Television; A Laboratory Experiment", AD919898, April 1974.

[62] Ciavarelli, A.; Wachter, L.; and Lee, W., "Terrain Classification Study", AD B005535, May 1975.

[63] Hall, E.; Hwang, J.; Lee, C.; and Hwang, M., "Measuring Scene Content From Aerial Images", SPIE, Vol. 186, pp. 215-223, May 1979.

Photographic Interpretation. Wolf[64] describes the basic characteristics of photographic images which are utilized for interpretation as:

a. Shape. This relates to the form configuration or outline of an individual object. Shape is probably the most important single factor in recognizing objects from their photographic images.

b. Size.

c. Pattern. The repetition of certain general forms or relationships is characteristic of many objects.

d. Shadows. Shadows in photographs have two general effects. They afford a profile view of the object casting the shadow and they hide objects within them.

e. Tone. Without tonal differences, shapes, patterns, and texture could not be discerned.

f. Texture. This is the frequency of tone change in the image. Texture is produced by an aggregate of unit features which may be too small to be clearly discerned.

g. Site. The location of an object in relation to other features may be very helpful in identification.

Photographic interpretation is not a skill to impart to a trainee in a real-time CIG system but the general characteristics listed above probably correlate well with the cues utilized by such a trainee as he observes his visual environment.

RECOMMENDATIONS

DETAIL SIZE

The amount of information necessary to model a visual environment extends from a maximum in which the display is indistinguishable from the real world to a minimum in which the display contains just enough visual cues to be perceptually similar for the specific task to be learned. The former case can be calculated from eye performance measurements and allowed closest approach. The size of the data base becomes enormous if the visual environment is to appear "realistic" for close approaches anywhere within the gaming area. The latter case is ideal in terms of economy but there is insufficient data available to define just what minimum amount of information is required for all tasks. A hypothesis is proposed as a strawman for scene detail requirements based on object acquisition studies described above.

---

[64] Wolf, P., "Elements of Photogrammetry", McGraw-Hill, New York, 1974.

Scene Detail Hypothesis. A visual environment need only be modeled to a level of detail sufficient to identify the object with the smallest critical minimum dimension for the particular visual tasks expected to be trained in the simulation system.

For example, if the scenario involves search and acquisition of targets no smaller than a tank and the minimum critical dimension of a tank is 2 meters then the visual environment should be modeled such that it appears indistinguishable from the real world when seen with 2 meters of object subtending 7 line pairs of resolution regardless of closest approach distance. In a CIG data base which incorporates different models of the same object, the above modeling criteria is pertinent to the highest level of detail modeled. In practice the modeler would work from tank photographs whose resolution is such that 7 line pairs could be resolved over a two meter distance at the same range as the tank. The modeler then adds detail to his model until the rendering of the CIG image resembles the tank image when they are both observed at the same size and resolution. It is proposed that the entire data base be constructed in this fashion although artificial detail at the 7 line pairs/2 meter criterion may be used as the highest texture spatial frequency in data base areas where specific scene content is not required.

This modeling technique would not appear realistic. For example, at a 5 meter closest approach 1 arc minute per line pair eye resolution implies 1400 line pairs/2 meters. The tank modeled by the 7 line pair/2 meters criterion would be devoid of expected details, however, it should still be capable of being identified as a tank which was the purpose for which it was intended. The justification for modeling the entire gaming area to this apparent detail is to make the background scene as complex as the smallest target at the identification level. This makes the entire acquisition sequence (from detection through identification) just as difficult in the simulation as in the real world.

Other mission scenarios might have different minimum critical dimensions. For example, consider a periscope view simulation. For identification of ship class a minimum critical dimension might be 50 meters but for determination of angle-on-the-bow the minimum critical dimension would be smaller.

DETAIL REFLECTANCE

Although the requirement for color has not been firmly established, it is proposed that detail spectral reflectance be recorded to eight bit precision in red, green, and blue primaries.

ENVIRONMENT CONTENT

The choice of which objects should be included in the simulated environment is somewhat subjective and task dependent. For example, a navigator would expect an environment to contain objects or features which are designated on the map he is using to navigate.

SECTION III

DATA BASE STRUCTURES

INTRODUCTION

This Section investigates the form of the representation of the environment which is operated on by the image generator to produce the visual display. Each representation class has its own advantages and disadvantages, which are strongly dependent on the class of objects or surfaces to be modeled. Before proceeding further, a distinction should be made between modeling and designing in the context of this report. Modeling is defined as generating a mathematical description of a real world environment. This is essentially a copying process. Designing, on the other hand, involves the subjective creation of a mathematical description. Modeling involves analyzing real world objects in terms of the chosen environment representation whereas designing involves synthesizing simulated real world objects using the chosen environment representation. Modeling does not require any intelligence or decision making and is highly amenable to automation.

Brown[65] describes the three basic problems of making a mathematical representation of physical solids, these are: (a) obtaining the raw data or physical measurements of the object; (b) representing the object description in a concise form; and (c) using the representation to render a display. The choice of representation is driven by both the means for obtaining the raw data and the means for rendering. There is no best representation which will be capable of efficiently accepting any form of raw data and efficiently rendering any type of object. Blinn[66] categorizes the most commonly used three-dimensional surface representation as; algebraic, point set, and parametric. Algebraic functions can be used to describe a limited number of object classes. The data stored in this case is the type of function, the coefficients which control it, and the region of the environment for which it is valid. Point set representations are the class to which current CIG data bases belong. The data stored in a current CIG data base are the three-dimensional locations of points (vertices) together with information concerning which points make up edges or lines, which edges make up polygons, and which polygons make up polyhedrons. This type of representation is best suited or most efficient for the representation of objects which have planar faces. The point set surface description class also includes those data base forms in which the surface to be modeled is sampled on a regular grid. In such a data base, two of the

---

[65] Brown, C. M., "Some Issues and Answers in Geometric Modelling" in Proceedings of Workshop on the Representation of Three-Dimensional Objects, Bajcsy, R. (ED.), The Department of Computer and Information Science, University of Pennsylvania, May 1979.

[66] Blinn, J., "Geometric Representations in Computer Graphics" in Proceedings of Workshop on the Representation of Three Dimensional Objects, Bajcsy, R. (ED.), The Department of Computer and Information Science, University of Pennsylvania, May 1979.

three dimensions of the vertex point locations are specified by memory location. The third class of surface description is the parametric representation. In this representation the surface is divided into a regular or irregular mesh of patches. The surface shape within a patch is then specified by an algebraic function of parameters which are chosen for their convenient behavior within the patch boundaries. In the case of the parametric representation, the data base would contain the location of the patch (in world coordinates) and the coefficients of the parametric equation describing the patch shape. The fidelity of the model to the surface being modeled is a function of the degree of the parametric function used (e.g. cubic, quadratic, quintic, etc.), the size of the patch, and the desired patch to patch continuity. An alternative data base format for parametric patch representation is the storage of three dimensional locations of control points which have the property of containing the information necessary to generate the parametric surfaces as the model is rendered.

Volume representations form another class of three-dimensional models. Objects are stored in the data base as conglomerations of primitive volume elements. The data base would include an object location and a listing of the type and relative location of the various volume elements required to render the object.

Higher order environment models include semantic models in which a data base entry might consist of an object name and its location.

Each of the above data base structures requires increasing complexity of the CIG processing system to render a display, as the structure class proceeds from algebraic, point set, and parametric surfaces to volume and semantic representations.

Some effort has been devoted to standardization of graphics systems. Bergeron[67] states that lack of standardization is the most serious obstacle to the widespread application of computer graphics. The Association for Computing Machinery is currently putting together a proposed standard for graphics (GSPC[68]). The only representation which was recommended to be a standard by the ACM Committee was the polygon made up of the three-dimensional coordinates of each of its vertices. There was no support given to the standardization of other than polygon representations . . . "at this time, since current systems are too diverse."

---

[67] Bergeron, R., "Standards for Interactive Computer Graphics Software" in Proc. of Workshop on Picture Data Description and Management, IEEE Computer Society, pp. 126-129, April 1977.

[68] "Graphic Standards Planning Committee Status Report", Computer Graphics, Vol. 13, No. 3, August 1979.

Clark[69] discusses desired attribute of a data base other than its structure, namely, a hierarchy of models having various levels of detail. Such hierarchal data bases have been implemented in CIG systems where it would be inefficient to operate on a data base which uses models at a high level of detail regardless of the simulated range. Thomason[70] applies this concept to a relational data base.

This section is only concerned with the types of representation used in computer graphics. Section IV will describe techniques for generating the data to make the model.

ALGEBRAIC SURFACES

A surface described solely by algebraic functions may potentially stretch to infinity. The degree of complexity of the surface is dependent on the complexity of the functions used to describe it. The higher the complexity of the functions the more difficult it is to render the model into a display. Planes are modeled by linear functions. In a rectangular coordinate system the general form for the equation of a plane is given by equation 3-1.

$$\text{3-1} \quad Ax + By + Cz + D = 0$$

The specification of the coefficients A, B, C, and D is sufficient to describe a model of a plane surface. Since plane surfaces in the real world do not stretch to infinity more information is required to model real world plane surfaces. This information can be in the data base or can be computed in the rendering process. For example, if the real world surface consists of two planes, the data base can specify the boundary line beyond which one of the planes is valid or the processing can determine the boundary by computing the line describing the intersection of the two planes.

The next degree of surface complexity which can be represented by algebraic functions are second degree polynomials of the form given by equation 3-2.

$$\text{3-2} \quad Ax^2 + By^2 + Cz^2 + Dxy + Exz + Fyz + Gx + Hy + Jz + K = 0$$

The types of surfaces capable of being modeled by this general equation are cylindrical surfaces (functions of just two of the three variables), conical surfaces (homogenous equations in the variables x, y, and z), spheres, ellipsoids, hyperboloids, elliptic paraboloids, and hyperbolic paraboloids. These surfaces and their various permutations make up the family of seventeen

[69]Clark, J., "Designing Surfaces in 3-D", Comm. of ACM, Vol. 19, No. 8, pp. 454-460, August 1976.

[70]Thomason, M., "Applications of Probalistic Information Theory to Relational Data Bases", SPIE, Vol. 186, pp. 224-229.

quadric surfaces. The modeling of surfaces in quadric and linear polynomials has been accomplished in non real time image generation systems for simulation of real world scenes (Gardner[71, 72], Yan[73], and Levin[74]).

The advantage of utilizing quadric models is the efficiency with which surfaces such as spheres, ellipsoids, etc. can be stored in the data base. The disadvantages of such representations are: (a) the complexity of the surface intersections which must be stored or computed (the intersection of two quadric surfaces is a fourth degree polynomial in the general case); and (b) the surfaces modeled are restricted to the seventeen quadric surfaces.

The representation of surfaces by equations of higher degree is potentially possible but difficult to implement due to the complexity involved.

POINT SET SURFACES

Polygons. In a point set surface representation the basic information stored in the data base is the three-dimensional location of points. All current real-time CIG systems employ point set surfaces as the preferred data base representation for modeling arbitrarily shaped real world objects. The specific type of point set representation used in these systems is one in which points are grouped to define edges, polygons and polyhedrons. The data base constructed for such CIG systems must conform to specific modeling rules imposed by the processing capabilities of the real-time hardware. Morland[75] describes the real-time CIG system at NAVTRAEQUIPCEN and the modeling rules which the modeler must follow if the environment is to be properly rendered. For example; polygon faces must be convex, the vertices making up the polygon face must be co-planar, the vertices must be numbered in a clockwise fashion when viewed

---

[71] Gardner, G., "Computer Image Generation System With Efficient Image Storage", in Optical Information Storage, SPIE, Vol. 177, pp. 10-12, 1979.

[72] Gardner, G., "Computer-Generated Texturing to Model Real-World Features", in Proc. of 1st Interservice/Industry Training Equipment Conference, pp. 239-246, November 1979.

[73] Yan, J., "Real-Time Generation and Smooth Shading of Quadric Surfaces", in Proc. of 1st Interservice Industry Training Equipment Conference, pp. 247-260, November 1979.

[74] Levin, J., "A Parametric Algorithm for Drawing Pictures of Solid Objects Composed of Quadric Surfaces", Communications of the ACM, Vol. 19, No. 10, pp. 555-563, October 1976.

[75] Morland, D., "System Description - Aviation Wide-Angle Visual System (AWAVS) Computer Image Generator (CIG) Visual System", Technical Report NAVTRAEQUIPCEN 76-C-0048-1, Naval Training Equipment Center, Orlando, Florida, February 1979.

from the visible side of the face, objects made up of convex polygons must be convex polyhedrons, objects are limited to a maximum of sixteen faces, and the number of edges in the environment as well as the number of edges in any potential field of view must not exceed the on-line storage capability or edge processing capability, respectively, of the real-time hardware. The polygon class of surface representation is most efficient for modeling real world objects composed of planar surfaces. The modeling of smoothly curved surfaces is less efficient with this technique since many polygons are required. This difficulty is somewhat overcome by the use of shading techniques in the rendering process which eliminate the appearance of edges on a polygon model of a smoothly curved surface. However, the silhouettes of such models will still have straight lines.

Many polygon oriented visible surface algorithms have been developed (Watkins[76], Sutherland[77]) and implemented in both real-time and non-real time image generators. The basic reason for such widespread use of this particular surface representation is the relative simplicity of the geometric transformations required for rendering a display on a flat screen such as a CRT monitor. This is summarized as; straight lines in the model transform to straight lines in the display. Carlbom[78] describes the variety of ways in which three-dimensional objects can be projected to a planar display. Polygon based image generators are continuously being refined to produce higher quality renderings. The latest developments involve the addition of texture to a polygon face (Bunker[79]) and the utilization of translucent faces (Bunker[80]).

Fixed Grid Arrays. The construction of a math model describing the relief of the earth's surface existed as a requirement long before there were CIG systems. Such math models of the earth's surface are called digital terrain models (DTM). The users of DTM have different requirements for the form of the terrain information. Geomorphologists prefer the DTM to be a set of

---

[76] Watkins, G., "A Real-Time Visible Surface Algorithm", AD-762004, June 1970.

[77] Sutherland, I.; Sproull, R.; and Schumacker, R., "Characterization of Ten Hidden-Surface Algorithms", Computing Surveys, Vol. 6, No. 1, pp. 1-55, March 1974.

[78] Carlbom, I and Paciorek, J., "Planar Geometric Projections and Viewing Transformations", Computing Surveys, Vol. 10, No. 4, pp. 465-502, December 1978.

[79] Bunker, W., "Computer Image Generation Imagery Improvement: Circles, Contours, and Texture", Technical Report AFHRL-TR-77-66, Advanced Systems Division, Air Force Human Resources Laboratory, Wright-Patterson Air Force Base, Ohio, September 1977.

[80] Bunker, W., "CIG Translucent Face Simulation Provides Multiple Benefits", Proc. of 1st Interservice/Industry Training Equipment Conference, pp. 229-238, November 1979.

contiguous non-overlapping polygons restricted to the horizontal plane whose boundaries are indicative of landforms. Surveyors prefer the representation of the terrain to be a polyhedral solid which approximates the terrain surface in three dimensions and adapts in density and complexity to the local topography. The cartographer prefers the terrain information to be in the form of lines such as profiles or contours. Despite the fact that none of the users of DTM desire the terrain model to be in the form of a regular grid of elevations, this is the form of terrain model which is most widely used (Mark[81]). Gridded data in which elevation is sampled at regular increments in latitude and longitude is inefficient. In order to have sufficient information to reproduce complex terrain the increments must be small but this implies a large number of samples even in areas where the terrain is flat. Dutton[82] points out the reasons for using gridded data even though it is inefficient. Gridded data is the easiest to generate since an automatic elevation measuring system does not have to make decisions on where to bound polygons. Gridded data is easiest to transport between different analysis systems; to compare one set of data with another; to display; and to conceptualize. Other advantages for graphics applications include: data access need not be global; and overlays can be accomplished with limited computational memory and inexpensive algorithms. For reasons such as these the Defense Mapping Agency, which is assigned overall responsibility of mapping, charting and geodetic resources in the Department of Defense, chose to use a regular grid representation for terrain elevation data (DMA[83]). A description of the DMA data base and an evaluation of its application to radar display simulation is given by Hoog[84] and Defense Mapping Agency Aerospace Center (DMAAC[85]). Salmen[86] surveys, assesses, and compares 54 existing computer software systems and geographic data bases. This report is indicative of the non-standardization of application programs which indicates the reason for desiring a data base form which is easily transportable.

---

[81]Mark, D., "Concepts of Data Structure for Digital Terrain Models", in Proc. of Digital Terrain Models (DTM) Symposium, American Society of Photogrammetry, May 1978.

[82]Dutton, G., "An Extensible Approach to Imagery of Gridded Data", Computer Graphics, Vol. II, No. 2, pp. 159-169, Summer 1977.

[83]Defense Mapping Agency, "Product Specifications for Digital Landmass System (DLMS) Data Base, PS/ICD-E-F-G/100, July 1977.

[84]Hoog, T.; Dahlberg, R.; and Robinson, R., "Project 1183: An Evaluation of Digital Radar Landmass Simulation", in Proceedings of NTEC/Industry Conference NAVTRAEQUIPCEN, IH-240, pp. 54-79, November 1974.

[85]Defense Mapping Agency Aerospace Center, "Test and Evaluation of USAF Project 1183 Digital Data Bases", DMAAC TR 79-1, February 1979.

[86]Salmen, L.; Gropper, J.; Hamill, J.; and Reed, C., "Comparison of Selected Operational Capabilities of Fifty-Four Geographic Information Systems", U.S. Department of Commerce, PB-286977, September 1977.

Many processing algorithms have been developed which utilize gridded data directly in creating imagery. Strat[87] utilizes an algorithm which takes a grid of elevation data and displays perspective or orthographic views in which pixel intensity is a function of surface normal and a simulated terrain illumination direction. Unruh[88] and Schachter[89] describe algorithms in which both elevation and spectral reflectance values in the grid data base are utilized to produce displays. Faintich[90] describes capabilities for generating displays in which elevation is a function of gray level, contoured displays, shaded relief displays, and stereo displays. Dungan[91] describes an algorithm implementation which can have several surfaces in gridded data format. Thus, visual effects such as clouds or haze can be generated from a grid data base.

Algorithms which transform gridded data into more efficient forms are described in Section 4.

PARAMETRIC SURFACES

This class of surface modeling divides the surface into patches whose location is specified in world coordinates. Within each patch the surface variation is described in terms of parametric functions chosen for their ability to efficiently model the surface within the patch. Planar patches are identical to the polygon point set representation. Quadric patches utilize quadric algebraic functions within a patch. The next level of surface complexity within a patch is that described by bicubic functions and so on. Forrest[92] gives a good summary of the various patch modeling and designing techniques. Depending on the specific patch technique used, the data base will contain

---

[87] Strat, T., "Shaded Perspective Images of Terrain", ADA055070, March 1978.

[88] Unruh, J.; Alspaugh, D.; and Mikhail, E., "Image Simulation From Digital Data", in Proceedings of American Congree on Surveying and Mapping, 1977.

[89] Schachter, B., "Computer Generation of Full Colored Textured Terrain Images", in Proc of 1st Interservice/Industry Training Equipment Conference, pp. 367-374, November 1979.

[90] Faintich, M.; Sigler, G.; and Fahy, D., "Digital Image Display and Simulation From Digital Terrain Data Bases", in Proc. of Digital Terrain Models (DTM) Symposium, American Society of Photogrammetry, pp. 610-616, May 1978.

[91] Dungan, W., "A Terrain and Cloud Computer Image Generation Model", Computer Graphics, Vol. 13, No. 2, pp. 143-150, August 1979.

[92] Forrest, A., "Recent Trends in Computer Aided Geometric Design", in Proc. of International Conference on Interactive Techniques in Computer Aided Design, IEEE Catalog No. 78CH1289-8C, pp. 141-146, 1978.

coefficients of the function within a patch or the location of control points which can be used to generate the proper surface shape. Some techniques utilize control points which are on the surface while others use control points which are remote from the surface. Brewer[93] describes patches which can be constructed from points on the surface. Quadric patches do not have enough degrees of freedom to satisfy slope continuity between patches for arbitrary surfaces but can be used where such continuity is not required. Mahl[94] describes algorithms for displaying surfaces made up of quadric patches. Algorithms for bicubic patches (Catmull[95, 96], Hosaka[97]) and biquintic patches (Munchmeyer[98]) have also been developed for displaying such surfaces. Wu[99] describes a technique for storing surface data as sectional curves (two-dimensional profiles of the surface sliced into parallel sections). His algorithm for displaying such a surface made up of B-spline functions interpolates between sections using cardinal spline functions, Blinn[100, 101] has developed a technique for applying texture to parametric patches which yields very impressive imagery. All of the patch display algorithms have one major drawback at this time: they are too computationally expensive to operate on a complex scene in real-time.

---

[93] Brewer, J. and Anderson, D., "Visual Interaction With Overhauser Curves and Surfaces", Computer Graphics, Vol. 11, No. 2, pp. 132-137, Summer 1977.

[94] Mahl, R., "Visible Surface Algorithms for Quadric Patches", AD-762017, December 1970.

[95] Catmull, E., "A Subdivision Algorithm for Computer Display of Curved Surfaces", ADA 004968, December 1974.

[96] Catmull, E., "Computer Display of Curved Surfaces", in Proc. of Conf. on Computer Graphics, Pattern Recognition, and Data Structure, IEEE Catalog No. 75CH0981-1C, pp. 11-17, May 1975.

[97] Hosaka, M. and Kimura, F., "Synthesis Methods and Curves and Surfaces in Interactive CAD", in Proc. of International Conference on Interactive Techniques in Computer Aided Design, IEEE Catalog No. 78 CH1289-8C, pp. 151-155, 1978.

[98] Munchmeyer, F. and Lau, G., "On the Iterative Design of Smooth Patched Surfaces", in Proc. of International Conference on Interactive Techniques in Computer Aided Design, IEEE Catalog No. 78CH1289-8C, pp. 147-150, 1978.

[99] Wu, S.; Abel, J.; and Greenberg, D., "An Interactive Computer Graphics Approach to Surface Representation", Communications of ACM, Vol. 20, No. 10, pp. 703-712, October 1977.

[100] Blinn, J., "Computer Display of Curved Surfaces", Ph.D. Thesis, University of Utah, December 1978.

[101] Blinn, J., "Geometric Representations in Computer Graphics" in Proceedings of Workshop on the Representation of Three Dimensional Objects, Bajcsy, R. (ED.), The Department of Computer and Information Science, University of Pennsylvania, May 1979.

VOLUME REPRESENTATIONS

Modeling solid objects can also be accomplished by representations in which the data base describes the objects as compositions of primitive solid building blocks. The simplest form of such a data base is a three-dimensional rectangular fixed grid of volume elements (Herman[102]). Braid[103] models objects as additions and subtractions of primitive solids such as cubes, wedges, and cylinders. Soroka[104] uses generalized cylinders as primitives. A generalized cylinder is stored in the data base as a location, an axis and a function which describes the cross section at each point along the axis. The University of Rochester Production Automation Project has generated a significant body of literature on solid modeling systems (Requicha[105], Voelcker[106], Brown[107]).

Volume representation can be very efficient in terms of data base storage requirements. The rendering of such data bases into displays is, in general, more complex and computationally expensive than surface representation.

SEMANTIC REPRESENTATIONS

The data base which stores information in the form of a high-level language is probably the most efficient model form. The words "blue '59 Chevy parked in front of a hospital" can certainly be rendered into a display by the human brain. The processing required by a computer to produce such a rendering from such information is difficult to conceive. Semantic models are useful,

---

[102]Herman, G. T., "Representation of 3-D Surfaces by a Large Number of Simple Surface Elements", in Proceedings of Workshop and Representation of Three-Dimensional Objects, Department of Computer and Information Sciences, University of Pennsylvania, May 1979.

[103]Braid, I., "The Synthesis of Solids Bounded by Many Faces", Communications of ACM, Vol. 18, No. 4, pp. 209-216, April 1975.

[104]Soroka, B. et al., "A Program for Describing Complex Three-Dimensional Objects Using Generalized Cylinders as Primitives", in Proceedings of IEEE Computer Society Conference on Pattern Recognition and Image Processing, pp. 331-339, June 1978.

[105]Requicha, A. and Voelcker, H., "Constructive Solid Geometry", U.S. Dept. of Commerce, PB281613, November 1977.

[106]Voelcker, H. and Requicha, A., "Geometric Modeling of Mechanical Parts and Processes", Computer, pp. 48-57, December 1977.

[107]Brown, C.; Requicha, A.; and Voelcker, H., "Geometric Modelling Systems for Mechanical Designs and Manufacturing", prepared for presentation at ACM 78, December 4-6 1978.

however, when the requirement is not to display in real-time but to organize a math model data base to allow it to be intelligently addressed by the modeler or processor. (McKeown[108], Agin[109]).

CONCLUSION

Brown[110] summarizes the characteristics of a good modeling system as (a) geometric coverage and tolerance (includes the capability to represent all shapes to the desired accuracy), (b) completeness (sufficient information about each object for current and future applications), (c) reliability (the system should be able to verify or guarantee the correctness of the data it contains), and (d) efficiency (the representation should be capable of supporting a variety of applications efficiently). Brown states that he knows of no geometric modeling system with these characteristics although a half-dozen or more are currently under development.

As far as current practical systems are concerned, point set data bases will continue to dominate CIG model representation. Regular grid models are easiest to generate automatically and polygon models are easiest to display with currently available technology.

---

[108] McKeown, D. et al., "A Hierarchical Symbolic Representation for an Image Data Base", in Proceedings of IEEE Computer Society Workshop on Picture Data Description and Management, pp. 40-44, April 1977.

[109] Agin, G. J., "Hierarchical Representation of Three-Dimensional Objects Using Semantic Models" in Proceedings of Workshop on the Representation of Three-Dimensional Objects, Bajcsy, R. (ED.) The Department of Computer and Information Science, University of Pennsylvania, May 1979.

[110] Brown, C. M., "Some Issues and Answers in Geometric Modelling" in Proceedings of Workshop on the Representation of Three-Dimensional Objects, Bajcsy, R. (ED.), The Department of Computer and Information Science, University of Pennsylvania, May 1979.

SECTION IV

DATA ACQUISITION AND REDUCTION

INTRODUCTION

The basic problem in modeling a real world environment is to transform real world data into a form or structure which can be recognized by the CIG system which uses the model. The ultimate source of the real world data is the real world but the data used by the modeler can already have been transformed into a non-CIG model and the problem can be one of transforming one representation into another.

Currently, the environment models utilized by real-time CIG systems are generated by tedious, manpower intensive techniques. The modeler utilizes data sources such as maps, photographs, scale drawings, and blueprints. The basic information obtained from these sources is the three-dimensional location of points in the real world and the spectral reflectance properties of surfaces in the real world. Based on the intended use and capacity of the CIG system the modeler makes subjective decisions on which points and surfaces should be included in the model. He then extracts the information from his data sources, puts the information in the form and structure required by the CIG system, and subjectively evaluates the imagery rendered by the CIG system using the model as a data base. Monroe[111] explains this process in great detail as implemented in the environmental model generation of what is the largest CIG data base existing. In actual practice many iterations of the above process are required before the modeler, the CIG system, and, possibly, the users are satisfied with the model. As the capacity of real time CIG systems continually grows, the size and complexity of the environmental model needed to support the CIG must grow. Dependence on the manpower intensive techniques is inadequate to support such growth in terms of efficiency and cost. Any techniques which can automate parts of the modeling process or reduce the amount of time required for the modeler to complete parts of the process should improve the overall efficiency of the process. Of course, the cost of the automation must be balanced against the cost of the modeler's time. The acquisition of position measurements from the real world environment can be accomplished by a variety of techniques (Fuchs[112]). The most elementary method is by direct, manual measurement. With the aid of yardsticks, plumb lines, and calipers a great many objects can be sucessfully measured. The modeler first determines what he considers to be points of interest on the object and then measures the coordinates of each of these points from a common reference position. The surface of the object is

---

[111] Monroe, E., "Environmental Data Base Development Process for the ASUPT CIG System", Air Force Human Resources Laboratory, Technical Report AFHRL-TR-75-24, August 1975.

[112] Fuchs, H., "The Automatic Sensing and Analysis of Three-Dimensional Surface Points From Visual Scenes", Ph.D. Dissertation available from University Microfilms, Ann Arbor, Michigan, 1975.

then defined as a topological net over these key points. The resulting model tends to be compact (since the modeler usually tries to minimize the number of points he must measure) and an effective representation of the object. This manual technique can be automated to some degree by substituting a machine for the yardstick and calipers. The machine can now perform the measuring function and the modeler need only designate the points of interest and their connectivity. Vickers[113] describes such a system in which a machine senses the three-dimensional coordinates of the tip of a wand. The modeler then touches the wand to a point on the object and indicates to the machine that it is a point of interest by activating a switch on the wand. This technique, like the purely manual technique, is time consuming and not practical for large complex objects or environments. However, it is effective for small, simple objects as long as the machine's "view" of the wand is not obstructed.

Fuchs[114] also discusses holographic and moire methods for data acquisition but the most practical data acquisition systems are based on multiple two-dimensional images. An entire technical field is devoted to this technique, stereo-photogrammetry. Stereo-photogrammetry is based on the fact that the location of the image of a point in a photograph defines a line along which the point must lie in the environment. Another photograph containing the same point but taken from another position defines another line. The location where the two lines intercept defines the point location. An obvious advantage of this approach is that there is no need for the modeler to decide on, or physically identify, the points of interest at the time the photographs are taken, since any point visible in both photographs can be located using the photographs alone.

There are many variations of the stereo technique. Fuchs[115] describes a computer controlled, random axis, triangulating rangefinder with a mirror deflected laser and revolving disc detectors. Sutherland[116] describes the utilization of a large area digitizing tablet with multiple pens to designate

---

[113] Vickers, D., "Sorcerer's Apprentices Head-Mounted Display and Wand", in Proc. of Symposium on Visually Coupled Systems: Development and Application, Brooks AFB, Aerospace Medical Division (Limited Distribution), pp. 522-540, November 1973.

[114] Fuchs, H., "The Automatic Sensing and Analysis of Three-Dimensional Surface Points from Visual Scenes", Ph.D. Dissertation available from University Microfilms, Ann Arbor, Michigan, 1975.

[115] Fuchs, H., "The Automatic Sensing and Analysis of Three-Dimensional Surface Points from Visual Scenes", Ph.D. Dissertation available from University Microfilms, Ann Arbor, Michigan, 1975.

[116] Sutherland, I., "Three-Dimensional Data Input by Tablet", in Tutorial on Computer Graphics, IEEE Catalog No. EHO-147-9, pp. 266-274, 1979.

the point of interest in multiple views of the same object. (The multiple views can extend in complexity from orthographic drawings to perspective photographs). Appel[117] prefers orthographic projections since there is a direct correspondence between the two-dimensional view and two of the coordinate axes in the data base.

The automation of stereo techniques requires that the machine be capable of determining which image points correspond to the same object points in multiple views containing the object. Such machines are currently used to produce digital terrain models. They are effective when the surface to be modeled is sufficiently textured in reflectance and yet sufficiently similar in two views that the machine can find the same point by correlation techniques. These sytems fail when the surface has large expanses of the same reflectance (such as deserts or lakes) or sufficiently rugged terrain that the views are too dissimilar to correlate, as the vertical side of a building which is visible in one of the images but invisible in the other.

Even if correlation techniques can generate the location of all points in a scene the modeler is still required to choose the points he wishes to include in his model (unless the form of his model is fixed grid). But techniques are available to assist him in this task. Digital and optical image processing technologies are capable (to a limited degree) of analyzing a scene in terms of its natural boundaries. Roberts[118] describes all of the elements of this process but the hardware sophistication at that time limited implementation to very simple scenes. Most of the application of these technologies has been in the area of machine recognition. Recognition implies that the machine contains a reference model of the object or objects it is required to recognize. The output of such a machine is the decision as to whether a reference object is in the scene as well as its location and orientation rather than the geometric description of an arbitrary object. Image processing techniques offer methods for analyzing 2-D images in terms of their natural boundaries. Optical image processing has inherent speed advantages over digital image processing. This has led to extensive research into applications where speed is required such as terminal guidance and threat identification (Neff[119]). The Navy has attempted to use this

---

[117] Appel, A., "Modeling in Three Dimensions", IBM Systems Journal, Nos. 3 and 4, pp. 310-321, 1968.

[118] Roberts, L., "Machine Perception of Three-Dimensional Solids", in Optical and Electro-Optical Information Processing, J. T. Tippett et al., EDS., MIT Press, Cambridge, Massachusetts, pp. 159-197, 1965.

[119] Neff, J. and Flannery, D., "Air Force Research in Optical Processing', in Optical Signal and Image Processing, SPIE, Vol. 118, pp. 2-5, 1977.

powerful tool several times with little success. (Trimble[120]). Vatz[121] states that the optical processing field better get moving if it is to compete in terms of size, cost, capability and utility with digital technology. Since speed is not of prime importance in modeling an environment for CIG systems, the digital processing technologies have the advantage and will be discussed in further detail in this report. The reader is referred to Casasent[122] and Nesterikhin[123] for further information on optical processing.

Software technologies also offer considerable assistance to the modeler. Digital data describing the geometry of an object or environment is already available in many cases. Programs which transform this available data into the CIG environmental model with little or no action required of the modeler can be implemented. The trend in both the civilian (Edson[124]) and military (DMA[125]) mapping communities is to record cartographic information in a machine readable form. The computer aided design community, as part of the design process, records object and shape descriptions in machine readable form. Besides techniques for recording real world data the modeler can use software techniques to assist in designing (rather than modeling). For example, the modeler can insert generically similar objects into the environment after modeling an object just one time. This is called object instancing.

In the remainder of this section, photogrammetry, digital image processing, artificial intelligence, and software modeling aids are discussed in greater detail. In Section V the applications of these techniques in terms of specific modeling tasks are discussed.

---

[120] Trimble, J., "Navy Optical Processing Programs for Systems Applications - An Historical Overview", in Optical Signal and Image Processing, SPIE, Vol. 118, pp. 96-99, 1977.

[121] Vatz, B., "The Moving Technology", SPIE, Vol. 118, Optical Signal and Image Processing, pp. 142-143, 1977.

[122] Casasent, D. ED., "Optical Data Processing Applications", Springer-Verlag, New York, 1978.

[123] Nesterikhin, Y.; Stroke, G.; and Kock, W., (Eds.), "Optical Information Processing", Plenum Press, New York, 1976.

[124] Edson, D. and Lee, G., "Ways of Structuring Data Within a Digital Cartographic Data Base", Computer Graphics, Vol. II, No. 2, Summer 1977.

[125] Defense Mapping Agency, "Product Specifications for Digital Landmass System (DLMS) Data Base, PS/ICD-E-F-G/100, July 1977.

STEREO PHOTOGRAMMETRY

Basics. Photogrammetry is the science of taking measurements from photographs. The two-dimensional location of an object's image in a photograph is directly related to its two-dimensional direction from the camera's location when the photograph was exposed. Measurements on the photograph are usually in rectangular coordinates called photograph coordinates. The units of photograph coordinates are usually microns. The real world direction of the object is usually computed as two angles, specifying a two-dimensional direction. The three-dimensional location of an object can be determined from the photographic coordinates of its image in two photographs which are taken from two different locations (stereo-photogrammetry). The procedures and geometry of photogrammetry duplicate the real world measurements and computations of a surveyor. Just as in surveying, there is a variety of instruments available to assist in the data acquisition and data reduction process leading to the production of a representation of the real world to the desired degree of precision.

The best known application of photogrammetry is the generation of maps and other cartographic products. In this application the photographs are usually aerial photographs. Aerial photos may be classed as vertical, in which the optical axis of camera is vertical and pointing down; low oblique, in which the optical axis is deviated from vertical but the recorded image does not contain the horizon; and high oblique, in which the horizon is contained in the recorded image. Most aerial photogrammetry utilizes vertical photography. Terrestrial photogrammetry connotes photography in which the camera is fixed to the ground. If the optical axis is perpendicular to the vertical direction the photographs are called horizontal photographs.

Single Photo. If the object being photographed lies in a plane perpendicular to the optical axis of the camera and the camera lens is free from distortion, the positions of image points in the photograph are directly related to positions on the object by a simple scale factor. Figure 1 shows such a situation.

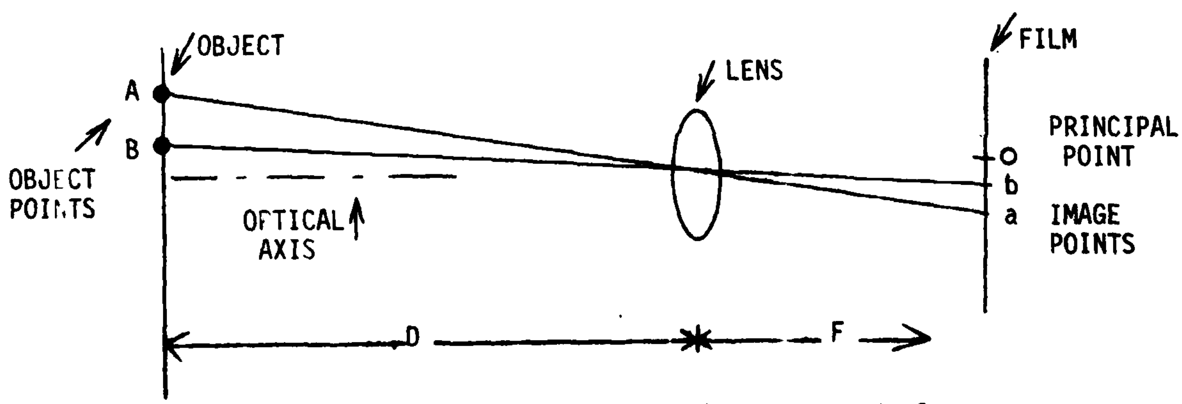

Figure 1. Image of a Planar Object Perpendicular to the Camera Axis

The scale of the photograph is the focal length (F) of the lens divided by the object distance (D), assuming object distance is much greater than the focal length. For example, a vertical aerial photograph taken from an altitude of 10,000 feet with a lens of focal length of 6 inches has a scale of 1:20,000. The physical distance measured on the photograph between image points a and b is equal to the physical distance between A and B in the object plane multiplied by the scale factor. Using the same example, if a and b are measured to be 1mm apart in photograph coordinates; A and B would be separated by 20 meters at the object plane.

Photogrammetry usually employs metric cameras for obtaining photographs. A metric camera has reference points, called fiducial marks, built into the focal plane which allow accurate recovery of the principal point of the photograph. The principal point is where the optical axis intercepts the image plane (marked "o" in Figure 1). A metric camera is manufactured specifically for dimensional stability. It is calibrated for focal length, coordinates of the principal point, and residual lens distortion.

Tilt. When the optical axis is deviated from the direction perpendicular to the object plane, the image points are displaced relative to their positions in the truly perpendicular case. Figure 2 shows this situation. A nominally vertical aerial photograph is usually tilted from vertical due to uncontrollable angular positions of the aircraft. The effect of tilt on image points can be compensated by utilizing control points to determine the pointing direction of the camera. Tilt can occur about two axes (for example, aircraft pitch and roll axes). The process in which the effects of camera tilt are eliminated is called rectification. Rectification only eliminates image point displacements for object points in the assumed object plane.

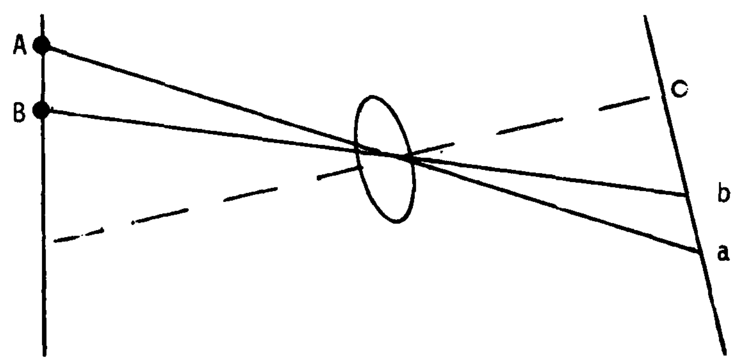

Figure 2. Effect of Tilt on Image Point Locations

Relief. Although a plane object surface can be assumed in many cases such as aerial photography of a flat terrain from a high altitude, the effect of surface relief or departure of the surface from a flat plane also causes image displacement.

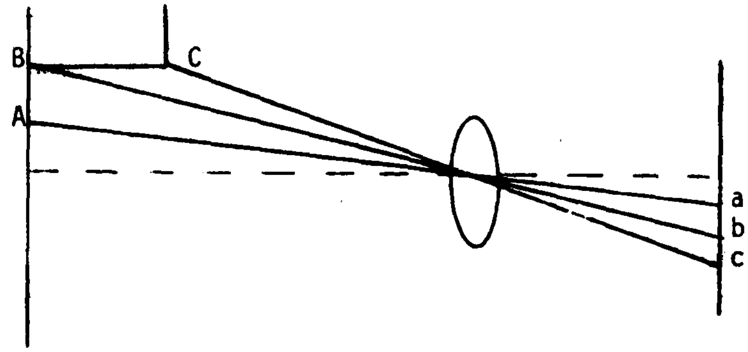

Figure 3. Effect of Surface Relief

The image displacement due to surface relief allows the relief to be computed if the distance to the object plane is known and the position of the relief point desired as projected into the object plane is known. In Figure 3 such a situation is pictured. Point C is the point whose relief distance is desired. Point B is the location of the intercept of the object plane generated by dropping a perpendicular from C to the object plane. Usually the location of Point B is an unknown and the single photograph method of surface relief measurement is not used. Another obvious effect of surface relief is that some parts of the surface are capable of being hidden by other parts of the surface. A not so obvious effect is that relief displacement will always be radially away from the point in the object plane intercepted by a perpendicular to the object plane dropped from the camera, regardless of camera tilt. In the case of aerial photography the point is called the nadir.

Stereo. The measurement or computation of surface relief utilizing two or more photographs taken from different viewing positions is stereo photogrammetry. The difference in image displacement of the same object point in the two photographs is called parallax. Figure 4 shows the geometry involved for the situation in which neither photograph has tilt (or has been rectified to remove tilt) and the distance D from the camera to the object plane is the same for both photographs.

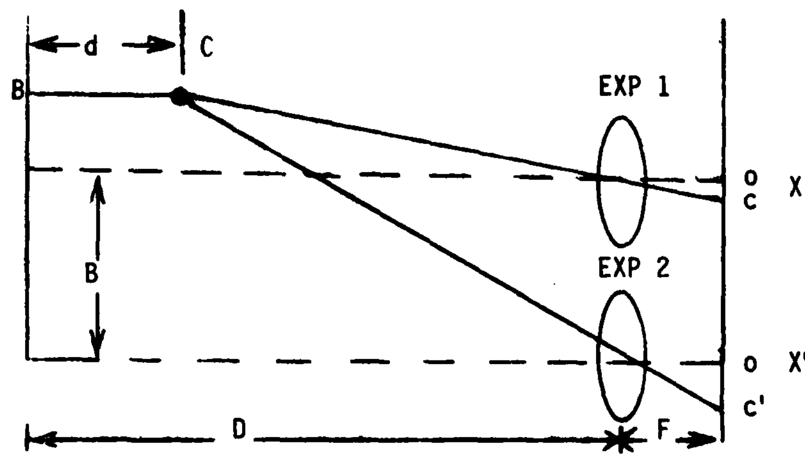

Figure 4. Stereo Geometry

In Figure 4, B is the length of the baseline or the distance between the camera exposure positions, C is the image of object point C on the two photographs, o is the principal point on each photograph, X and X' are the distances measured on the photographs between the principal points in a direction parallel to the baseline. The difference X-X' is called the parallax (p). From similar triangle relationships it can be shown that the relief distance d = BC is given by equation 4-1.

$$4\text{-}1. \qquad d = D - \frac{B\,F}{P}$$

In aerial photography the greatest single obstacle in utilizing the relatively simple relationships between parallax and relief is the presence of tilt in the photographs. Terrestrial photographs are easier to analyze since the location of the camera and its pointing direction can be precisely measured at the time of exposure using standard surveying techniques.

Other Factors. There are several other factors which can cause image displacement besides tilt and relief. These are: motion of the camera relative to the object during an exposure, inherent distortion in the camera lens, stability of the principal point with respect to the fiducial marks or other references, departure from flatness of the film at the time of exposure, thickness and resolution of the film, stability of the film against dimensional changes during processing and handling, and atmospheric conditions at the time of exposure.

Photogrammetric Terms. There are several other terms used in photogrammetry which are of interest. The ratio of the length of the baseline (distance between exposure stations) to the object distance is called the base-height ratio. The larger the base height ratio, the greater the parallax and the smaller stereo overlap. In typical aerial photography, base height ratios of 0.6 are common. In close range photogrammetry, base height ratios of 0.2 are common. The instrument or method used to make photogrammetric measurements are usually classified by a quality factor called the "C" factor. The "C" factor is the ratio of object distance to the accuracy with which relief can be measured. "C" factors range from approximately 500 to 5000 depending on the quality of the instrument and the photographs. For example, an instrument being used to generate terrain elevations from aerial photographs might have a "C" factor of 1,200. This indicates that height of the terrain could be measured to within 10 feet if the aerial photographs were shot from an altitude of 12,000 feet. Convergent photogrammetry describes photogrammetric measurements made from photographs taken with the optical axes purposely tilted. Convergent photogrammetry is used when the base height ratio is desired to be large so that parallax is large and easy to measure but the coverage or overlap of the photographs is also desired to be large. The overlap area of two photographs defines the area of the stereo model within which parallax can be determined. The area within the stereo model which is actually used for measurements is called the neat model. Photogrammetric measurements are usually made from positive transparencies of the negatives exposed in the camera. These are called diapositives.

Photogrammetric Instruments. The determination of the geometry of a three-dimensional object from photographs utilizes instruments which fall into two general classes; instrumental and analytic. Although both classes utilize instruments, the differences in the techniques used to recover the three-dimensional description from the photographs are different. Both methods require that a sufficiently dense network of control points or reference points be acquired from the object. Large-scale (objects are large in photographs) photography generally requires more control points than small-scale photography.

Instrumental Vs. Analytical Photogrammetry. Instrumental photogrammetry is defined as the instrumental process of establishing three-dimensional locations of object points from visual, spatial models. The models are formed in instruments called stereoplotters which physically reverse the photographic process to create a small-scale, three-dimensional model of the surface which was photographed. Measurements can be made directly from the model without extensive mathematical computation. Figure 5 shows the basic arrangement of a projection plotter. The two diapositives are mounted in a dual projector. The projected images are viewed in stereo by an operator.

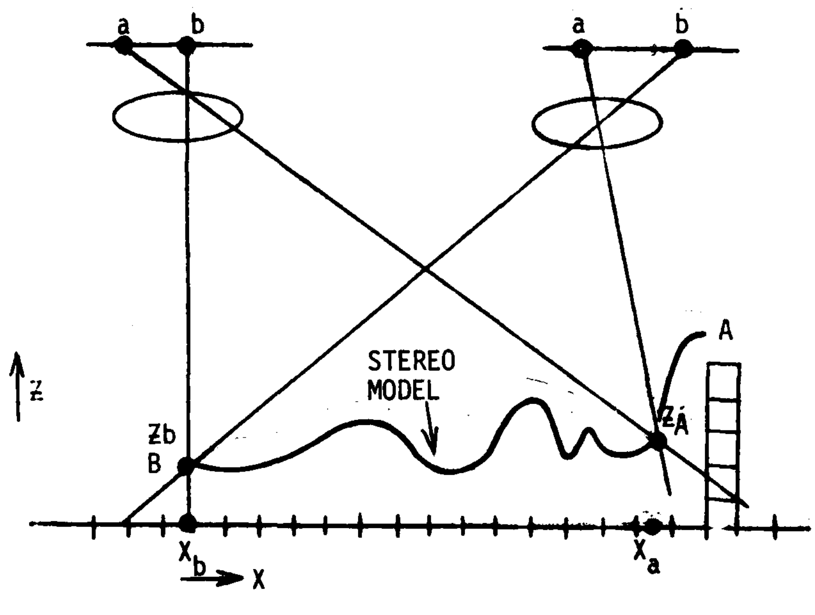

Figure 5. Projection Plotter

In order to allow only one projected image to be seen by each eye of the observer the light is usually coded in some way, e.g., by color or polarization. The images are projected such that the stereo model apparently floats in space above the surface of a table. In Figure 5 an object A is recorded at

different positions in the two diapositives. Rays from each of the diapositives of the image of object A will intersect or be coincident at point A in the stereomodel. By using a table which is capable of measuring X position (in this simplified two-dimensional example) and an elevation stage capable of measuring height above the table the coordinates of the point of coincidence can be directly measured. The true coordinates can then be found by simply multiplying by the scale of the stereomodel relative to the actual object size. Such instruments are commercially available which generate digitized x, y, z coordinates of any point in the stereo model within the limits of the instrument. The limitations imposed by the use of such instruments are dictated by their physical construction; e.g., mechanical limits of stage movements, limits on variation of scale, limits on format size, etc. Analytical instruments determine the object point location by computation involving the measured location of the image points of the same object in the two photographs and the various parameters associated with the original photography.

The advent of relatively inexpensive computers has made analytic photogrammetry the preferred method in recent years. The fundamental advantage of analytic photogrammetry is that there are no limitations or restrictions on the geometry of the original photography due to the geometry of the measurement process.

Automatic Stereocompilation. The basic parameter desired to be measured is parallax. This requires that the same object can be recognized by the instrument in both photographs. In non-automatic methods the human operator performs this recognition function. Automatic instruments, on the other hand, must perform the recognition function without the aid of an operator. The technique used in automatic instruments is to correlate an area of one photograph with areas of the other photograph until a correlation peak is obtained. For objects which lie in a plane or deviate from a plane only by a small amount, this technique works well and has been implemented in the generation of terrain relief information from small-scale aerial photographs. In such photographs the earth's surface is essentially flat and the appearance of an object in the two photographs is nearly identical allowing a high correlation peak to be found. Problems arise with this technique when high correlation cannot be found or cannot be located to the desired accuracy in the photograph. Some examples of problem areas are: featureless areas in the photographs, such as featureless plains or bodies of water in the case of aerial photography, and areas of high relief where the differences between the two photographs are too great to correlate. An automatic instrument can be taught to overcome these problems to some degree. For example, a body of water is recognized as such and assigned the elevation of its shoreline. The use of epipolar geometry also aids in automatic correlation. Epipolar lines are lines on the photographs defined by the intersection of the photograph planes with planes which contain both photograph perspective centers (epipolar planes). The perspective center corresponds to the location of the camera lens when the photograph is made. More specifically, the perspective center for the photograph image is the rear nodal point of the lens. For any particular epipolar

plane, conjugate imagery in the two photographs appears along conjugate epipolar lines. By scanning the photographs along epipolar lines the image correlation task is reduced from two-dimensional to one-dimensional. Automatic stereo compilation equipment is used extensively in the cartographic community. In general, the use is restricted to small-scale aerial photography. The "C" factor of such equipments is in the range of 5,000. Areas where correlation is difficult, due to lack of features or ground slopes in excess of 60°, are generally beyond the instrument capabilities and require the assistance of a human operator to do the recognition task. Additional detail on the subject of photogrammetry may be obtained from Thompson[126] and Wolf[127]. A description of automatic stereo compilation techniques are described by Helava[128] who invented the analytic plotter. Descriptions of commercially available automatic equipments are also available (Bendix[129], Abshier[130], Kraus[131], VanWijk[132], Allam[133], Kelly[134]). Typical performance of an automatic system is the production of a 700,000 point digital terrain model and an orthophoto in 90 minutes (Kelly[135]).

---

[126] Thompson, M. (Editor), "Manual of Photogrammetry", American Society of Photogrammetry, Falls Church, VA, 1966.

[127] Wolf, P., "Elements of Photogrammetry", McGraw-Hill, New York, 1974.

[128] Helava, U., "Instruments and Methods for Digital Terrain Model Data Collection", in Proc. of the Digital Terrain Models (DTM) Symposium, American Society of Photogrammetry, pp. 61-71, May 1978.

[129] Bendix Research Laboratories, "Photogrammetry at Bendix", Bendix Center, Southfield, Michigan, 48076.

[130] Abshier, J., "TA3/PA and AS-11B-1 Improvement Study", AD904906L, September 1972.

[131] Kraus, K.; Otepka, G.; Loitsch, J.; and Haitzmann, H., "Digitally Controlled Production of Orthophotos and Stereo-Orthophotos", Photogrammetric Engineering and Remote Sensing, Vol. 45, No. 10, pp. 1353-1362, October 1979.

[132] VanWijk, M., "Geometrical Quality of Stereo-Orthophotos Produced From Automatic Image Correlation Data", Photogrammetric Engineering and Remote Sensing, Vol. 45, No. 10, pp. 1363-1369, October 1979.

[133] Allam, M., "DTM's Application in Topographic Mapping", in Proc. of Digital Terrain Models (DTM) Symposium, American Society of Photogrammetry, May 1978.

[134] Kelly, R.; McConnell, P.; and Mildenberger, S., "The Gestalt Photomapping System", Photogrammetric Engineering and Remote Sensing, Vol. 43, No. 11, pp. 1407-1417, November 1977.

[135] Kelly, R.; McConnell, P.; and Mildenberger, S., "The Gestalt Photomapping System", Photogrammetric Engineering and Remote Sensing, Vol. 43, No. 11, pp. 1407-1417, November 1977.

Orthophotography. The production of an orthographic perspective view from a pair of stereo photographs is called orthophotography. The orthophotograph is essentially a photograph in which the image displacement due to relief has been removed. All object image points in the orthophotograph have photograph coordinates which directly correspond to coordinates of the object in the object plane. In the case of aerial photography the object plane coordinates might be latitude and longitude. In this case relief is elevation and a point on the orthophotograph is associated with a single latitude-longitude value regardless of the terrain elevation at that point. Orthophotographs can be produced opto-mechanically or analytically.

Digital Photogrammetry. Many digital computational techniques are being investigated and implemented in the field of photogrammetry. Most of these involve the conversion of a photograph into a form recognizable by a computer. This is generally accomplished by quantizing the density or transmission of the photograph at discreet, digitized locations in photograph coordinates. The digitizing and quantizing operations will be discussed in the section on digital image processing. The resultant digital image is a mathematical entity which can be manipulated by a computer (Rosenfeld[135]). Panton[136,137] describes a technique for producing digital terrain models from digital images utilizing epipolar geometry for correlation search strategies. He also recommends the utilization of bi-cubic patch models based on a rectangular grid for surface description. Hunt[138] presents a simplified theory of the relation between errors in calculation of terrain elevation and the observable parameters in a digitized stereo pair. Keating[139] gives the computer memory storage requirements for a digitized stereo pair of 9" aerial photographs as 5 X 10^8 bits together with the resultant model storage requirement of 10^8 bits. Keating[140] also describes the procedure to produce an orthophoto from an unrectified aerial photo and a digital terrain model.

---

[135] Rosenfeld, A., "Extraction of Topological Information From Digital Images", ADA042125, June 1977.

[136] Panton, D., "Digital Orthophoto Study", ADA020066, December 1975.

[137] Panton, D., "A Flexible Approach to Digital Stereo Mapping", in Proc. of Digital Terrain Models (DTM) Symposium, American Society of Photogrammetry, pp. 32-60, May 1978.

[138] Hunt, B. and Ryan, T., "Prediction of Correlation Errors in Parallax Computation From Digital Stereo Images", in Applications of Digital Image Processing, SPIE, Vol. 149, pp. 222-231, August 1978.

[139] Keating, T., "Analytical Photogrammetry From Digitized Image Densities", Ph.D. Dissertation, University of Wisconsin, 1975, (Avail. NTIS).

[140] Keating, T. and Boston, D., "Digital Orthophoto Production Using Scanning Microdensitometers", Photogrammetric Engineering and Remote Sensing, Vol. 45, No. 6, pp. 735-740, June 1979.

Close Range Photogrammetry (CRP). CRP is not amendable to automatic operation since the relief is large and corresponding images are usually too different to be correlated. Large relief also makes analytic photogrammetry more advantageous than instrumental photogrammetry. Karara[141] and Jaksic[142] describe the hardware and software available for close range photogrammetry. An interesting application of CRP is found in Liebes[143].

Color Orthophotography. Once the relief of a surface has been determined, any type of photographic imagery can be transformed into an orthophoto. Konecny[144] describes a procedure for producing true color orthophotos. Martin[145] describes the production of false color orthophotos from visual and near IR photos.

Non-Metric Cameras. If a sufficient number of control points are known, the distortions and lack of registration information associated with ordinary cameras can be compensated in making photogrammetric measurements. Abdel-Aziz[146] has implemented such an approach with the conclusion that photographs taken with a $20 hand-held camera were capable of generating position information accurate to 2mm for an average object distance of 5 meters ("C" factor of 2,500). His analysis indicates that a minimum of 6 object control points are required and near co-planar control points should be avoided. This indicates that with proper analysis techniques and some knowledge of the dimensions and location of the object one can take any camera and simply take several photographs of it to obtain three-dimensional coordinate information.

---

[141] Karara, H., "Industrial Photogrammetry", in Proc. of Symposium on Close-Range Photogrammetric Systems, American Society of Photogrammetry, pp. 97-141, July 1975.

[142] Jaksic, Z., "Analytical Instruments in Close-Range Photogrammetry", in Proc. of Symposium on Close-Range Photogrammetric Systems, American Society of Photogrammetry, pp. 538-555, July 1975.

[143] Liebes, S. and Schwartz, A., "Viking 1975 Mars Lander Interactive Computerized Video Stereophotogrammetry", Journal of Geophysical Research, Vol. 82, No. 28, pp. 4421-4429, September 1977.

[144] Konecny, G., "Methods and Possibilities for Digital Differential Rectification", Photogrammetric Engineering and Remote Sensing, Vol. 45, No. 6, pp. 727-734, June 1979.

[145] Martin, S., "Color Image Maps From Black and White Photographs", Photogrammetric Engineering and Remote Sensing, Vol. 46, No. 2, pp. 193-200, February 1980.

[146] Abdel-Aziz, Y. and Karara, H., "Photogrammetric Potentials of Non-metric cameras" University of Illinois at Urbana, PB-231-254, March 1974.

FEASIBILITY

An evaluation of stereophotogrammetry applied to generating a polygon model was made using a scale model of a ship. The scale model was photographed from two positions using a metric camera. A projection stereoplotter was then used to digitally determine the three-dimensional coordinates of operator chosen vertices of polygons. This data was then manually keyed into a computer aided design work station in the format required by the NAVTRAEQUIPCEN CIG system. (This step would not be necessary if the stereo analysis equipment were interfaced directly to the modeler's display). Since the ship model was symmetrical about a vertical plane, only one side had to be digitized. The resultant wire frame model is shown in oblique perspective in Figure 6.

A comparison of this technique to manual digitizing methods cannot be made since the cost of manually generating three-dimensional vertices has not been analyzed. The cost of the stereo method can be estimated as follows for a typical airport environment containing approximately 10,000 vertices: Non-recurring - stereo-plotter and computer graphics display $100,000; recurring costs - aerial photography and ground control $5,000; plotter set-up (36 stereo pairs) $1,000 and digitizing time $5,000.

DIGITAL IMAGE PROCESSING

Basics. A digital image is an image which has been discretized both in spatial coordinates and luminance. A digital image may be considered as a matrix whose row and column indices identify a point in the image and the corresponding matrix element value identifies a gray level at that point. The elements of such a digital array are called picture elements or pixels (Gonzalez[147]). Digital image processing consists of mathematically manipulating digital images to extract information. The two principal applications of digital image processing are the improvement of pictorial information for human interpretation and the processing of picture data for autonomous machine perception. The basic elements of a digital image processing system, utilized as an aid to picture interpretation, are a digitizer, a digital computer, and a display. The digitizer converts the image into a machine recognizable form, the computer performs the desired mathematical manipulations and the display converts the results into an operator readable form.

Digitizers. The conversion of a continuous tone image such as a photograph into a digital image is accomplished by a digitizer. Digitizers are most commonly either scanning microdensitometers or television cameras. Microdensitometers are used when high precision is required and the input image is in the form of a transparency. TV cameras are more flexible in terms of the form of the input data, less precise, and faster than microdensitometers.

---

[147] Gonzalez, R. and Wintz, P., "Digital Image Processing", Addison-Wesley Publishing Co., Reading, Massachusetts, 1977.

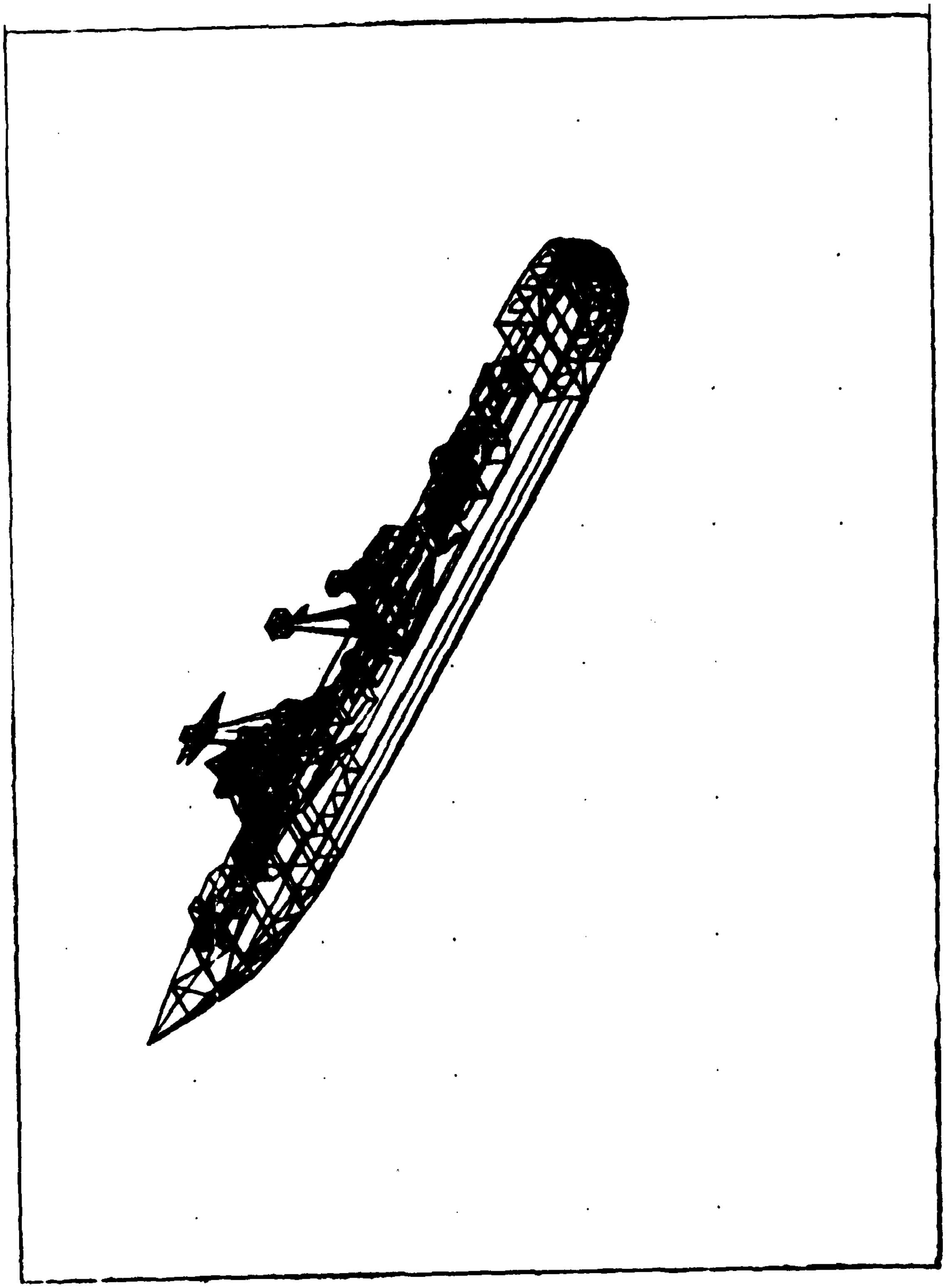

Figure 6. Wire Frame Model From Stereophotos

Both types of systems use a photosensor to sense the light level from each point in the image. The light level is then assigned a quantized gray level representing the pixel. The gray level assigned can be linearly or non-linearly related to the output of the photosensor. Therefore, some "analog" processing can occur before the picture is digitized. The effect of analog processing on the image is similar to the effect of changing brightness or contrast on a broadcast television picture. Color digitizing is accomplished by the use of color filters, monochrome color separations, or color sensitive photodetectors. The sample or pixel size to which the original imagery is discretized is not independent of the original imagery. The discrete sampling of imagery leads to aliasing effects or the generation of spurious spatial frequencies unless the spatial sampling is at least twice the resolution of the original imagery (Nyquist criterion). Therefore, the original imagery digitizing process must consider aliasing and its effect on the desired result. Typical microdensitometers can digitize a photograph containing a quarter of a billion pixels quantized to 256 gray levels (8 bits) in a few hours. A TV digitizer can digitize a TV frame of approximately one quarter million pixels in a TV frame time of 1/30 second.

<u>Digital Computer</u>. The function of the digital computer in a digital image processing system is to perform some operation or operations on the mathematical entity which is the digitized image. The operations range from the relatively simple operations used for image enhancement to extremely complex operations used for pattern recognition and machine understanding or artificial intelligence. Pratt[148] is an excellent reference for the various types of operations which are performed on digital images.

<u>Displays</u>. The display of the results of the processing operations are dependent on the desired end product. For example, a processor might be an image enhancer whose function it is to provide a "better" version of the input image to the operator. A more complex processor might have the function of determining whether a particular object's image is contained in the input image in which case the output is a yes, no, or maybe. For the modeling application of interest, the display would most likely be a raster scanned Cathode Ray Tube (CRT), preferably a color shadow mask type, with some operator interaction capability.

<u>Image Enhancement Operations</u>. The most basic operations of digital image processing are those which operate on single pixels without regard to the remainder of the pixels in the image.

<u>Histogram</u>. The production of a histogram is perhaps the most basic operation. A histogram is simply a count of how many pixels in the image have a particular gray level. The resultant plot which may be displayed to the

[148] Pratt, W., "Digital Image Processing", John Wiley and Sons, New York, 1978.

operator on a CRT display or output in hard copy from a plotter would resemble Figure 7.

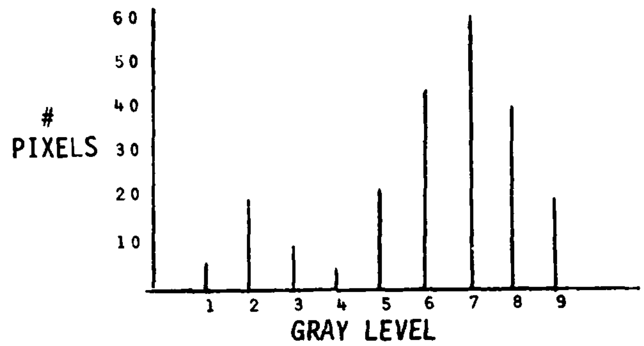

Figure 7. Histogram

Histogram analyses do convey some information about a digitized image. For example, the histogram envelope might indicate that the image belongs to a certain class of images or that the image should undergo additional processing. In the case of multispectral images, e.g., color separations, each image has its own histogram.

Contrast Stretching. The digital image process which assigns different gray levels to each pixel so as to make optimum use of the gray level range of the display is called contrast stretching. For example, the histogram of an image (as originally digitized) might be concentrated in only a few adjacent gray levels. The contrast stretching operation would reassign the few adjacent levels to displayed gray levels which are separated to the gray level limit of the display. Figure 8 shows the result of such an operation by comparing the histogram of input image to the histogram of the displayed image.

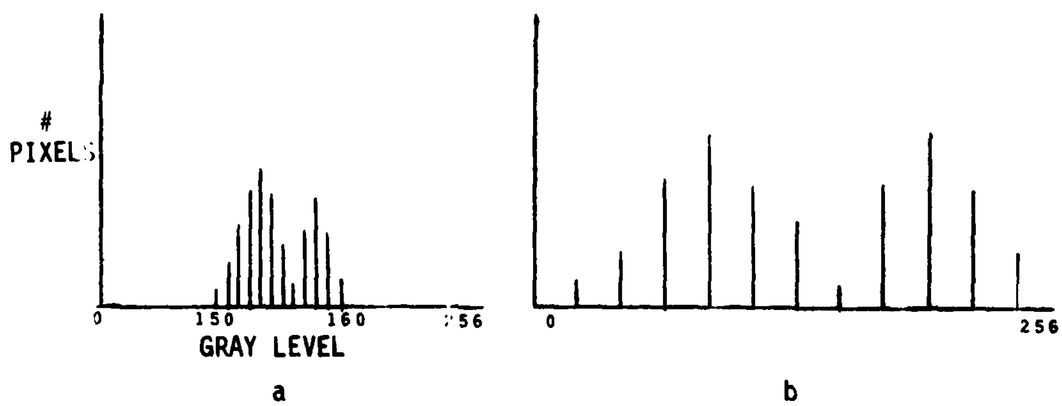

Figure 8. Contrast Stretching (a) Input Image Histogram (b) Displayed Image Histogram

The result of this operation is to enhance the contrast of the original image. Figure 8 represents a linear form of contrast stretching. Non-linear stretching might also be used. For example, the histogram of the original image might contain two widely separated peaks with few pixels having gray levels outside these two regions. In this case the maximum utilization of the displayed pixels might be a linear stretch of the first peak over half the available gray levels while the second peak is spread over the other half of the available display levels. Figure 9 shows the histograms of the input and output images.

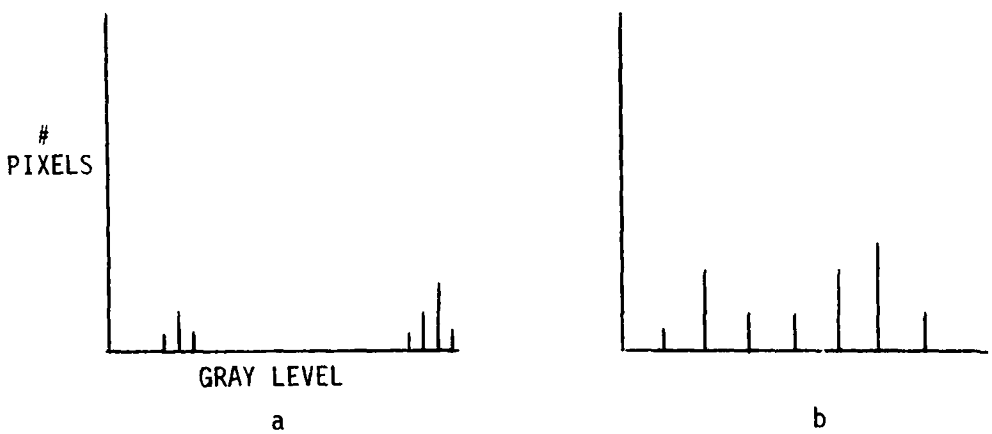

Figure 9. Non-Linear Contrast Stretching (a) Input Histogram, (b) Output Histogram

Another single pixel operation which is used to modify the histogram of a digitized image is clipping. Clipping involves the clipping off of the high and low gray levels and then stretching the remaining gray levels. Clipping is used when there is little or no desired information in these extreme areas of the image histogram. Clipping from just one side of the histogram is called thresholding.

Operations which select only a small range of gray levels for display are called gray level slicing. The display of a sliced image can be stretched to fill the available display gray level range or can be displayed as a binary image where whites or grays are used to display only those pixels in the original image which are contained in the slice.

If the display is capable of color, the digitized monochrome image can be pseudo colored to assist the operator in extracting information. Three color displays are also required to simultaneously view a color image generated from three monochrome images. Level slicing can be accomplished in each image independently or by considering all three (or more) monochrome digitized images. These techniques comprise multi-spectral image classification.

The most widespread utilization of the above techniques is to classify terrain areas in aerial or satellite images according to surface material. A Landsat image, for example, contains approximately 8 million pixels, each of which has 4 gray levels associated with apparent brightness in 4 different spectral bands. Each pixel in each band is quantized to a precision of 6 or 7 bits. The total number of different values (or 4-vectors) which a pixel can have is in excess of 100 million. Jayroe[149] in analyzing a typical Landsat image found that one third of the pixels were unique (there were no other pixels in the image which had the same 4-vector). Another eighth of the pixels were duplicated once. The most common vector was associated with 3,000 pixels. Jayroe stated that some landsat images such as those taken of a vegetated terrain during a growing season had as many as 99% of the pixels with unique vectors. Despite such classification statistics an operator can perform useful classifications to a high degree of accuracy with sufficient iterations on the type of contrast stretching and level slicing employed. Ground truth measurements or the obtaining of information regarding the specific material contained within a ground area covered by a specific pixel is important if the classification is to accurately reproduce the location of real world surface materials. Problems encountered in classification by histogram analysis are primarily due to the gray level or multispectral signature (combination of gray levels from several spectral bands) not being the same for the same material in different images (such as photographs made at different times or from different locations, or with different cameras etc.). Even in a single photograph the same type of material may have different signatures in different parts of the image (Nagao[150]).

Noise Cleaning. Digital images can also be processed by considering the local neighborhood around a pixel and modifying the gray level of the displayed pixel, based on the gray levels of the pixels around it. By appropriate choice of algorithms the effect of such operations could be to low pass spatial filter the image which minimizes high spatial frequency noise or to high pass filter the image and emphasize edges or high spatial frequency information. Another alternative is to transform the image into a sum of spatial frequency components and display the pixels which have the particular spatial frequency relations of interest.

Noise in an image is usually of high spatial frequency. Low pass filtering is accomplished by performing an average or weighted average of the pixel in the digital image with its 8 nearest neighbors (or 15 or 24 nearest neighbors) and assigning the corresponding display pixel the average value. For example, an average of a white noise spot pixel gray level = 256, in a black background, neighboring pixel gray levels = 1, using an equally weighted filter over the

---

[149] Jayroe, R. and Underwood, D., "Vector Statistics of LANDSAT Imagery", NASA Tech Memo, TM 78149, December 1977.

[150] Nagao, M. et al, "Agricultural Land Use Classification of Aerial Photographs by Histogram Similarity Method", Proceedings of IEEE Computer Society Conference on Pattern Recognition, pp. 669-672, November 1976.

white pixel and its 8 nearest neighbors produces a display pixel of gray level = 29. Other noise cleaning masks might assign a weight of 2 to the pixel of interest and a weight of 1 to the neighboring pixels or a weight of 4 to the pixel of interest and weights of 2 and 1 to its immediate neighbors respectively. The result of noise cleaning tends to lose resolution since the operation reduces contrast of high spatial frequency information as well as reducing noise contrast.

Edge Enhancement. Edges or high spatial frequency information in a digital image can be extracted or utilized to enhance the original image. This is accomplished by taking the difference between a pixel and its neighbors and assigning the gray level of the displayed pixel based on the difference. By analogy to the noise cleaning operation a weighted average is computed for each pixel with negative weights assigned to the neighbors while a positive weight is assigned to the pixel of interest. An operation like this can be utilized along a row or column of the digital image matrix and so extract vertical or horizontal edges independently. Similarly, by appropriate weighting of neighbors edges, running in any or all directions can be extracted. The operation which is concerned with any difference is called a gradient operation (since the form of the displayed image is approximately the gradient of the original image). Applying the gradient operation to a gradient image is called a Laplacian operation. Original images tend to be subjectively better when their own Laplacian is added to them. The resultant image appears crisper to the human observer.

Besides improving the asthetic qualities of an image, the above operations also tend to simplify more complex image processing operations which require some machine understanding of the image structure. The more complex operations are almost always preceded by the relatively simple operations of histogram modification, noise reduction, and edge enhancement.

Image Restoration. When the original image has been degraded due to some known mechanism, the image can be restored to some degree by processing it to remove the degradation due to the known cause. Andrews[151] and Pratt[152] contain detailed information on the types of image degradation and image restoration operations. Some sources of image degradation which are amenable to restoration techniques are diffraction in the optical system, sensor non-linearities, optical system aberrations, film non-linearities, atmospheric turbulence, image motion blur, geometric distortion, sensor or film noise, and temporal effects. Digitizing the original imagery can also be a source for image degradation which can be counted in the processing.

[151] Andrews, H. and Hunt, B., "Digital Image Restoration", Prentice-Hall Inc., New Jersey, 1977.

[152] Pratt, W., "Digital Image Processing", John Wiley and Sons, New York, 1978.

In practice a math model of the degradation process is developed and a process derived from the model which will invert the degradation. It is apparent that such processing can become extremely complex if many degradations are present. The specific restoration processes are not independent and the order in which they are applied is important.

The conclusion to be drawn is that original imagery should contain little or no degradation and the original image digitizing system should be designed to minimize degradation in the digitizing process. The assumption that a degraded image can be restored is optimistic and the better procedure would be to eat the degraded image and obtain another original when possible and practical.

Image Understanding. The above operations require no understanding on the part of the machine. The machine just operates on one image to produce another. The technology which is involved with the design of machines which can extract information from the data available, make inferences as to the high-level structure of the information, test those inferences, and learn from mistakes is called artificial intelligence (Hunt[153], Winston[154], Jackson[155]). The design of such machines tends to be analogous to mental perception processes. The digitized image or scene is analyzed into segments or regions based on some parameter such as gray level (or color) or gray level variation within the region. Such scene analysis is natural to biological visual perception processes. Each region is then classified as the image of a known object (recognition) or as the image of a new object (cognition) or as irrelevant information. Machines which are capable of such processes have been implemented with some success in limited applications (Kasvand[156]). The applications usually involve scenes of limited complexity or classification to a limited number of object types.

Segmentation. The data in a digital image is gray level or color for each pixel. The information which is to be extracted from this data can take many forms and so there are many varied paths used to arrive at the desired information. One of the most basic operations in scene analysis is to segment the scene into regions within which the gray level or some function of gray level describes the pixels to the desired degree of fidelity. Once a scene has been segmented, the boundaries of each region can be mathematically described. The boundaries of a region can be used to describe the shape of a region to the machine. Shape is a higher order description which may be the desired information or may be the input into a recognition process which matches or correlates shapes.

---

[153] Hunt, E., "Artificial Intelligence", Academic Press, New York, 1975.

[154] Winston, P. (Editor), "The Psychology of Computer Vision", McGraw-Hill Book Company, New York, 1975.

[155] Jackson, P., "Introduction to Artificial Intelligence", Petrocelli/Charter, New York, 1974.

[156] Kasvand, T., "Some Observations on Linguistics for Scene Analysis", in Proceedings of IEEE Computer Society Conference and Computer Graphics, Pattern Recognition, and Data Structure, pp. 118-124, May 1975.

The most elementary segmentation algorithms analyze a scene by dividing it into regions having the same gray level. In the case of multispectral images, the regions have the same color. The analysis of landsat imagery is amenable to this type of classification (Towles[157]). Problems arise when differences in gray level or color do not arise from surface material differences but from lighting, sensor, or atmospheric effects. A digital image segmented by gray level into a binary image can be transformed into a line drawing type of image by a gradient operation. In all but the most simple images, this will result in the display of many unconnected lines of various lengths and orientations in which the boundaries of the various scene regions are imbedded. Techniques for eliminating or minimizing the extraneous lines include region filling. Region filling of the binary gray level slice is accomplished by changing the value of a pixel if all of its surrounding neighbors have a different value. This is done prior to the gradient operation to remove single pixel anomalies. Many similar techniques are utilized in scene analysis algorithms (Duda[158]).

Segmentation can be accomplished by doing a gradient operation then growing a region by connecting line segments or edges extracted by the gradient operation to surround regions.

Discrimination of regions by texture classification is a more sophisticated process. Classification of terrain from aerial photographs has been studied by Weszka[159]. He found that the best measure of texture was based on second order statistical differences. Tamura[160] analyzed scenes according to those texture properties which resemble human perception processes. Segmentation and texture classification has also been described by Tou[161] and Haralick[162] among many others.

---

[157] Towles, R., "An Experimental Approach to Generation of Digital Landmass Data Base Culture/Planimetric Files Using LANDSAT Imagery and Multispectral Image Analysis Techniques", Proc. American Society of Photogrammetry, Fall Technical Meeting, October 1977.

[158] Duda, R. and Hart, P., "Pattern Classification and Scene Analysis", John Wiley and Sons, New York, 1973.

[159] Weszka, J.; Dyer, C.; and Rosenfeld, A., "A Comparative Study of Texture Measures for Terrain Classification", IEEE Trans on Systems, Man, and Cybernetics, Vol. SMC-6, No. 4, pp. 269-285, April 1976.

[160] Tamura, H., "Textural Features Corresponding to Visual Perception", IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-8, No. 6, pp. 460-473, June 1978.

[161] Tou, J. etal., "Picture Understanding by Machine Via Textural Feature Extraction", in Proceedings of IEEE Computer Society Conference on Pattern Recognition and Image Processing, pp. 392-399, June 1977.

[162] Haralick, R.; Shanmugam, K.; and Dinstein, I., "Textural Features For Image Classification", IEEE , Trans. on Syst., Man, and Cybernetics, Vol. SMC-3, pp. 610-621, November 1973.

Once an image has been segmented into meaningful regions, the shape of the region or the content of the region can be further analyzed.

Pattern Recognition. The technology of automatically recognizing a gray level distribution within a region or the shape of a region as belonging to one of a number of classes is called pattern recognition. Once a scene has been segmented, a variety of algorithms are available to assist in the recognition process (Agrawala[163]). Davis[164] provides a survey of techniques used to find edges. Hueckel[165] and Duda[166] describe algorithms for locating lines and edges based on gray level. Nevatia[167] used color for edge detection and scene segmentation.

The edges bounding a region may be obvious to a human operator but the machine must also be capable of knowing edges if it is to know the shape of the region. Nevatia[168] describes an algorithm which finds groups of edges that connect in a straight line and then links them to form a boundary. Agin[169] describes an algorithm which finds roads in an aerial photograph. Hwang[170] uses both global and local edge information to locate region boundaries enabling the machine to interpolate through image areas where the edge may be hidden. Once the machine has what is essentially a line drawing of the scene, it can proceed with the recognition of description process. This may involve templet matching in which case the machine has a stored library of specific

---

[163] Agrawala, A., "Machine Recognition of Patterns", IEEE Press, John Wiley and Sons, Inc., New York, 1976.

[164] Davis, L., "A Survey of Edge Detection Techniques", Computer Graphics and Image Processing, Vol. 4, pp. 248-270, 1975

[165] Hueckel, M., "An Operator Which Locates Edges in Digitized Pictures", Journal of the Association of Computing Machines, Vol. 18, pp. 113-125, January 1971.

[166] Duda, R. O. et al, "Use of the Hough Transformation to Detect Lines and Curves in Pictures", Communications of the Association for Computing Machines, Vol. 15, pp. 11-15, January 1972.

[167] Nevatia, R., "A Color Edge Detector and its Use in Scene Segmentation", IEEE Trans. on Systems, Man, and Cybernetics, Vol. SMC-7, No. 11, pp. 518-524, November 1977.

[168] Nevatia, R., "Locating Object Boundaries in Textured Environments", IEEE Trans on Computers, Vol. C-25, No. 11, pp. 1170-1175, November 1976.

[169] Agin, G. et al., "Interactive Aids for Cartography and Photo-Interpretation", ADA056355, June 1978.

[170] Hwang, J.; Lee, C.; and Hall, E., "Segmentation of Solid Objects Using Global and Local Edge Coincidence", in Proceedings of IEEE Computer Society's Conference on Pattern Recognition and Image Processing, pp. 114-121, August 1979.

templets which can be compared to the regions found. Another alternative is to utilize templets of generic features to interrogate the image. Each region shape will have a particular signature when operated on by all of the feature extractors. If the reference object has been characterized by a particular feature signature, then regions could be classified by comparing their signatures with the reference signatures. By application of pattern recognition techniques, many two-dimensional region shapes can be classified. However, unless all potential object images are known prior to processing, there will be an "unknown" class, even if their is no "noise" or mistakes in the edge extraction process. Despite the fact that scene analysis has not been perfected for an arbitrary two-dimensional image, investigators have proceeded to three-dimensional scene analysis.

Three-Dimensional Scene Analysis. This can be divided into single-view and multiple-view scene analysis. The single-view class can be based on matching a stored object description as seen from various viewing directions against the projected boundary in the available view. Brooks[171] describes a system which is supplied with generic descriptions of objects in a high-level modeling language (objects are segmented into generalized cones). Views of the stored objects are then matched to the information obtained from scene processing. McKee[172] describes algorithms which operate on an edge image to define surfaces bounded by edges. In subsequent views, each edge is compared to previously stored edges or assigned as a new edge. This system can then recognize or learn. Hemami[173] works from objects whose silhouettes can be found and compared to the shape of regions. Guzman[174] first finds and classifies vertices (edge intersections) in an image of a group of polyhedrons. By applying his algorithm, the machine can perform a three-dimensional scene segmentation. Some investigators have utilized distance information acquired by some other means such as a laser rangefinder (Duda[175], Nevatia[176]) to allow the task of object recognition or three-dimensional scene analysis to be simplified.

---

[171] Brooks, R. A. et al., "Progress Report on a Model Based Vision System" in Proceedings of Workshop on the Representation of Three Dimensional Objects, Bajcsy, R. (ED.), The Department of Computer and Information Science, University of Pennsylvania, May 1979.

[172] McKee, J. and Aggarwal, J., "Computer Recognition of Partial Views of Three Dimensional Curved Objects", in Proc. of Conference on Pattern Recognition, IEEE Catalog No. 76 CH1140-3C, pp. 499-503, November 1976.

[173] Hemami, H.; Weimer, F.; and Advani, J., "Identification of Three-Dimensional Objects by Sequential Image Matching", IEEE, Proc. of Conference on Computer Graphics, Pattern Recognition, and Data Structure, Catalog No. 75CHO 981-1C, pp. 273-278.

[174] Guzman, A., "Computer Recognition of Three-Dimensional Objects in a Visual Scene", Ph.D. Thesis, Massachusetts Institute of Technology, December 1968.

[175] Duda, R. et al., "Use of Range and Reflectance Data to Find Planar Surface Regions", IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. PAMI-1, No. 3, July 1979.

[176] Nevatia, R. and Binford, T., "Description and Recognition of Curved Objects", Artificial Intelligence, Vol. 8, pp. 77-98.

The three-dimensional scene analysis class which utilizes more than one view of the scene includes stereo photogrammetry. This class also includes the description of scenes or recognition of objects all of whose surfaces are not visible in any of the multiple views. Zucker[177] divides the scene space into volume elements he calls voxels. His algorithm then determines the orientation of a plane that separates volumes of different voxels when different views are used. Della Vigna[178] and Henderson[179] describe algorithms which describe three-dimensional scenes composed of planar objects. Della Vigna states that the most crucial problem is identifying the same vertex in two different views. Nevatia[180] and Lacina[181] describe algorithms which track the same object point in multiple images. Nevatia's technique utilizes many different views to track the same point with measurement only needing those views at the extremes of visibility. Potmesil[182] illuminates the object with a projected grid. His algorithm then finds the same grid intersections in the different views. This works well as long as all grid intersections are visible in at least two views. Shapira[183] describes an algorithm which constructs a description of a three-dimensional scene from multiple views by assuming that objects are composed of planar or quadric surfaces and all vertices are formed by exactly three faces.

---

[177] Zucker, S. and Hummel, R., "An Optimal Three-Dimensional Edge Extractor", in Proceedings of IEEE Computer Society's Conference on Pattern Recognition and Image Processing, pp. 162-168, August 1979.

[178] Della Vigna, P. and Luccio, F., "Some Aspects of the Recognition of Convex Polyhedra From Two Plane Projections", Information Sciences, Vol. 2, pp. 159-178, 1970.

[179] Henderson, R.; Miller, W.; and Grosch, C., "Automatic Stereo Reconstruction of Man-Made Targets", SPIE, Vol. 186, pp. 240-248.

[180] Nevatia, R., "Depth Measurement by Motion Stereo", Computer Graphics and Image Processing, pp. 203-214, May 1976.

[181] Lacina, W. and Nicholson, W., "Passive Determination of Three Dimensional Form From Dynamic Imagery", SPIE, Vol. 186, pp. 178-189, May 1979.

[182] Potmesil, M., "Generation of 3-D Surface Descriptions From Images of Pattern-Illuminated Objects", in Proceedings of IEEE Computer Society Conference on Pattern Recognition and Image Processing, pp. 553-559, August 1979.

[183] Shapira, R. and Freeman, H., "Computer Description of Bodies Bounded by Quadric Surfaces From a Set of Imperfect Projections", IEEE Trans. on Computers, Vol. C-27, No. 9, pp. 841-854, September 1978.

Summary. The application of digital image processing techniques to environment modeling must be restricted to automated rather than automatic operation at the present time. Automatic technique development has been and will continue to be driven by applications where a human operator cannot be utilized and so the technology will eventually be available to the CIG modeler with or without his support. Currently digital image analysis and processing techniques can greatly aid the modeler with relatively simple algorithms and operations which do not require a high degree of machine sophistication. For example, weighted averaging can allow the operator to observe an object at various resolution levels; digitizers can determine appropriate colors of scene elements; three-dimensional geometry of objects or vertices can be determined from multiple views with the operator indicating the same point in each view.

FEASIBILITY

The digital image processing facility at Kennedy Space Center was visited and a small experiment was conducted. A color aerial photograph of an urban area was digitized into three-digital images using a television digitizer with three color filters. The three images were then processed together and separately to determine whether the machine could readily extract regions which were very apparent to the human observer. The features chosen were lakes and major roads. The techniques used were histogram analysis for the lakes and both histogram analysis and gradient operations for the roads. In neither case did the processing reduce the time it would have taken for an operator to manually digitize those particular features using the same image on a digitizing table. Admittedly, the image was complex and the processing algorithms utilized were relatively simple. But the fact remains that an experienced operator of the equipment required at least an hour to create a major road map on the display. The same map could be created from the original image and a digitizing tablet in less than 10 minutes. The relative ease with which colors of regions could be determined does allow digital image processing to be a viable assistance to the modeler.

SOFTWARE TRANSFORMATION

In many cases the information required to construct an environment model already exists in some machine recognizable form. The prime example of this is digital terrain models which have been assembled for cartographic purposes. Such digital terrain models are usually derived from automated stereo photogrammetric instruments in the form of fixed grid point sets. Although the fixed grid format is used in some digital terrain models most transform the fixed grid into an irregular grid. Fowler[184] describes a procedure for transforming a fixed grid to an irregular triangular network. The difficulty encountered with

[184] Fowler, R. and Little, J., "Automatic Extraction of Irregular Network Digital Terrain Models", Computer Graphics, Vol. 13, No. 2, pp. 199-207, August 1979.

this procedure is insuring the capture of important topographical features such as ridge lines and stream beds. In practice these must be added manually. Jancaitis[185] converts a fixed grid digital terrain model into polynomial patches using a least squares criteria. Patch size is determined by how well the polynomial fits the points within the patch. Other transformation techniques have been or are being developed for the creation of radar and visual data bases from fixed grid digital terrain models.

Since object contours or cross sections can be generated in many ways, a software transformation from contour information is also desirable. Fuchs[186] has developed a technique which will tile the surface of a three-dimensional object whose cross sections are simple closed curves with triangular polygons. The tiled surface generated is valid at all of the given contours to a given precision.

Although this report is primarily concerned with the modeling of a real world environment, there is some advantage to having a system with which the operator can sculpt objects rather than copy existing objects. Parent[187] describes the sculptor's studio environment of the Computer Graphics Research Group at Ohio State University.

Besides transformation programs another important software function is the bookkeeping required to insure that the modeled environment conforms to the requirements of the real time CIG system. For example, Monroe[188] describes the limitations imposed on a polygon data base in terms of the maximum number of potentially visible edges from any one viewpoint as well as the maximum number of edges per object. The number of closed convex polyhedral objects which can be grouped to form a model is limited. The number of objects and the number of models within the field of view and range of view is also restricted. With proper software parameters, edge, object, and model counts can be monitored by the machine so that the real time CIG capacity is not exceeded by the environment complexity.

The development of transformation and bookkeeping software is highly system specific and not in the scope of this report.

---

[185] Jancaitis, J. and Moore, W., "Near Real-Time Application of Digital Terrain Data in a Mincomputer Environment", AD-A054008, April 1978.

[186] Fuchs, H.; Kedem, Z.; and Uselton, S., "Optimal Surface Reconstruction From Planar Contours", Communications of the ACM, Vol. 20, No. 10, pp. 693-702, October 1977.

[187] Parent, R., "A System for Sculpting 3-D Data", Computer Graphics, Vol. II, No. 2, pp. 138-147.

[188] Monroe, E., "Environmental Data Base Development Process for the ASUPT CIG System", Air Force Human Resources Laboratory, Technical Report AFHRL-TR-75-24, August 1975.

SECTION V

SYSTEM RECOMMENDATIONS

INTRODUCTION

This section discusses the recommended design of an environmental data base generation facility which utilizes the tools and techniques discussed in the previous sections. The basic information to be recorded in the data base is assumed to be geometric and appearance parameters. Current systems which are utilized to generate environments will be described, followed by a discussion of the application of stereo photogrammetric and digital image analysis techniques to automating the tedious operator tasks. Finally, a recommended approach to improving the efficiency of the environment data base generation facility at the NAVTRAEQUIPCEN will be proposed.

CURRENT SYSTEMS

Morland[189] describes the environment data base generation system developed by General Electric for the NAVTRAEQUIPCEN. It was designed to provide the capability of generating environments specifically for the real time CIG system at NAVTRAEQUIPCEN. It consists of three major subsystems; a digitizer station, a non-real-time CIG emulator, and a camera station. The digitizer station consists of a digitizing table, which provides the two-dimensional coordinates of a point on the table indicated by an operator with an electronic pen, and an interactive graphics display system which is capable of displaying perspective views of wire frame models whose three-dimensional vertex locations and connectivity have been supplied by the operator either through the digitizing of several two-dimensional views of a scene (usually orthographic views in the form of blueprints) or by operator insertion of coordinates through a keyboard or by modifying a previously digitized vertex by use of the digitizing tablet, an electronic pen, and a cursor on the display. Once the modeler has generated and viewed the displayed wire frame model and is satisfied with its appearance, edge count, and object count, he is ready to record an object or model for the CIG data base. The type of information needed for an object description is; a unique object name, a designator as to whether it's two-dimensional or three dimensional, the number of vertices, the number of polygon faces, and the face data (coordinates of vertices and color). Model descriptions include the type of model, the names of the objects composing it, the way in which the objects join, the level of detail as a function of range, the size of the model, its orientation, and priority information. An environment description includes the name, the names of the models within the environment, the location and orientation of the models within the environment, special codes for sun angle illumination, and surface color blending. The real-time CIG emulator is a minicomputer programmed to duplicate the perspective transformations and hidden surface algorithms implemented in the real-time CIG hardware at NAVTRAEQUIPCEN. The rendered

[189] Morland, D., "System Description - Aviation Wide-Angle Visual System (AWAVS) Computer Image Generator (CIG) Visual System", Technical Report NAVTRAEQUIPCEN 76-C-0048-1, Naval Training Equipment Center, Orlando, Florida, February, 1979.

imagery is then fed to a film recording station which utilizes a monochrome, high-resolution CRT imaged onto recording film. Three exposures through color filters serve to produce a color image for evaluation.

Schnitzer[190] describes the data base development facility utilized by Singer-Link to provide environments for the Singer real-time CIG system. He describes the construction of a CIG environment using the DMAAC DLMS data base, culture files (DMA[191]). The culture files consist of a plan view of the earth's surface in which polygons define cultural feature boundaries in a high-level language description. The process utilized by Schnitzer semi-automatically generates three-dimensional environments from these two-dimensional polygons. The example cited utilized a culture file of much higher density than the standard DLMS product; 4300 vertices in one square mile. The concept to simply "extrude" each polygon into a three-dimensional object is powerful and can be done fairly automatically for objects with vertical sides. However, there are many cases where the feature information must be supplemented by the modeler using other sources.

Black[192] describes the environment generation techniques employed by Evans and Sutherland for their CIG systems. A digitizing tablet is the prime source of vertex coordinate determination from which wire frame models are made. The wire frame model is interactively modified by the modeler. Software routines are used to transform line drawings to polygons and to define solid objects.

A software routine allows the modeler to create a polygon tiled surface of revolution by just specifying a two-dimensional curve and the number of polygons desired.

The development of three-dimensional graphics environments primarily for non-real-time graphics systems has been accomplished at several universities. Clark[193] discusses the sculpting methods employed at The University of Utah. The novel system described employs a head mounted display and a three-dimensional wand. The sculptor simply moves the wand about to create the environment which he then observes in three dimensions as his inputs are

---

[190] Schnitzer, A., "A Data Base Generation System for Digital Image Generation", in Proc. of 9th NTEC/Industry Conference, pp. 103-113, November 1976.

[191] Defense Mapping Agency, "Product Specifications for Digital Landmass System (DLMS) Data Base, PS/ICD-E-F-G/100, July 1977.

[192] Black, S., "Digital Processing of Three-Dimensional Data to Generate Interactive Real-Time Dynamic Pictures" in Three-Dimensional Imaging, SPIE, Vol. 120, 1977.

[193] Clark, J., "Designing Surfaces in Three-Dimensional", Comm. of ACM, Vol. 19, No. 8, pp. 454-460, August 1976.

rendered. Clark concludes that three-dimensional interaction is far superior to standard design techniques for three-dimensional environments. Greenberg[194] discusses the facilities at Cornell University. He describes four methods of interactively building an environment; assembling conglomerations of primitive volumes, utilizing multiple two-dimensional views, utilizing serial cross-sections, and extruding two-dimensional shapes. He recommends that all of these tools be available to the modeler. Hackathorn[195] describes the facilities of the Computer Graphics Research Group at the Ohio State University. Based on the descriptions of existing systems and available data acquisition technologies, the characteristics of an optimum environment data base generation facility can be defined together with implementation recommendations.

INTERACTIVE SYSTEMS

Schneiderman[196] describes the general policies to be considered in designing interactive systems. These are summarized in fairly general statements based on human factors experiments. Interactive systems should be simple to operate but perform powerful operations. The operational procedures should be easy to learn and yet appeal to experienced users. Errors should be handled easily but freedom of expression should not be restricted. The system development time should be as short as possible with low cost and capability for future modifications. Although these statements are general, Schneiderman does give some specific recommendations. The maximum response time should not exceed one or two seconds for simple user commands. In no cases should the response time exceed 15 seconds. In the case of environmental modeling, a simple command might be a vertex entry. A complex command might involve changing the viewpoint and look direction for a rendered environment.

Recommendation. The interactive facility should be capable of rendering a display of a modified environment in less than 15 seconds. This requirement precludes the utilization of a film writer as the display means. The preferred method of display is a CRT monitor having visual characteristics emulating the display utilized in the real-time system and sufficient computation power to render an image in less than 15 seconds.

---

[194] Greenberg, D., "An Interdisciplinary Laboratory for Graphics Research and Applications", Computer Graphics, Vol. 11, No. 2, pp. 90-97, Summer 1977.

[195] Hackathron, R., "ANIMA II: A Three-Dimensional Color Animation System", Computer Graphics, Vol. II, No. 2, pp. 54-64, Summer 1977.

[196] Shneiderman, B., "Human Factors Experiments in Designing Interactive Systems", Computer, pp. 9-19, December 1979.

DISPLAY SYSTEMS

Latta[197] analyzes display design both from the standpoint of display operator and from the limitations imposed by the state-of-the-art display hardware. He concludes that a 14-inch square display having 1,024 x 1,024 pixels viewed from a distance of 4 feet meets the acuity and comfortable viewing distance requirements of the observer. The implementations of this recommendation requires some tradeoffs based on available displays. A 19" high-resolution color shadow mask CRT having 980 raster lines is probably the best alternative. A more standard monitor (normal 525 line TV) would be less expensive but require a viewing distance beyond the comfortable range if acuity is to be maintained. A 2,048 x 2,048 display requires an uncomfortably close viewing distance if the display acuity is to be utilized. Carlson[198] lists 30 requirements for graphics terminals and evaluates available graphics terminals as inadequate for all but 12 of his requirements. Hubble[199] provides a survey and feature comparison of ten commercially available real-time color digital image displays. The utilization of more than one display monitor in a system allows stereo viewing or multiple operators. For stereo viewing on a single monitor Roese[200] describes a field sequential stereo display which is utilized with PLZT ceramic stereo glasses. The glasses are commercially available. Ohlson[201] surveys various devices for allowing an operator to interface with the interactive system. These include digitizing tablets, touch panels, joysticks, and trackballs. The use of horizontal tablets or other devices which allow the operator to rest his arm are preferable to the use of light pens which must be positioned on the vertical surface of the CRT from the standpoint of reducing operator fatigue.

Recommendation. Operator station should consist of at least two display monitors; a color monitor having the capability of rendering imagery equivalent in color and acuity to the display driven by the real-time CIG, and a monochrome computer terminal type display for alphanumeric interaction with the system. Operator controls should include a digitizing tablet or joystick as well as a standard terminal keyboard. The capability to view renderings in stereo can be achieved through the field sequential stereo method noted above.

---

[197] Latta, J., "New Developments in Digital Image Processing Displays", SPIE, Vol. 164, pp. 164-171, 1977.

[198] Carlson, E., "Graphics Terminal Requirements for the 1970's" in Tutorial on Computer Graphics, IEEE Catalog No. EHO-147-9, pp. 126-134, 1979.

[199] Hubble, L. and Reader, C., "State of the Art in Image Display Systems", SPIE, Vol. 199, pp. 2-8, August 1979.

[200] Roese, J., "Stereoscope Computer Graphics for Simulation and Modelling", Computer Graphics, Vol. 13, No. 2, pp. 41-47.

[201] Ohlson, M., "System Design Considerations for Graphics Input Devices", in Tutorial on Computer Graphics, IEEE Catalog No. EHO 147-9, pp. 282-290, 1979.

STEREOPHOTOGRAMMETRIC EQUIPMENT

Although digital terrain models are available from sources such as the Defense Mapping Agency and the U.S. Geological Survey, as well as high-level language descriptions of type and class of cultural features as a function of geographic location, there are still a large number of shapes in the real world whose geometric descriptions do not exist in a digitized form. For this reason, stereophotogrammetric techniques, specifically that class of photogrammetry known as close range or terrestrial photogrammetry, offer a means for assisting the modeler. The function of the stereophotogrammetric equipment would be to produce a geometric description of a specific cultural object from stereo photographs. In many cases such a specific model could be used as a generic model which can reside in a feature library to be called up, modified appropriately, and inserted into the environment. The type of equipment required includes a camera for initial image acquisition and an analytical stereo plotter interfaced to the system computer. In operation, the camera system would be used to take stereo photographs of the desired object from a sufficient number of viewpoints to insure complete stereo coverage. A number of object control points would be recorded at the same time. The analytic stereo plotter would then be used to create the stereo model. The operator would input the various control parameters to properly orient the stereo model. The three-dimensional coordinates of any operator selected point on the three-dimensional image of the object could then be automatically recorded. By using the keyboard, the operator can group vertices as belonging to specific polygons and polygons as belonging to specific objects etc.

Although stereophotogrammetric analysis systems based on the utilization of two television images have been implemented (Yakimovsky[202], Liebes[203]), the greater resolution of film based systems and the lack of need for rapid raw data acquisition precludes their use for this application.

The speed with which an operator can digitize stereo models is a strong function of the relief and relief variation in the model. Speakman[204] describes a task in which 21,035 points were encoded in 56 operator hours. If the stereo model is amenable to automatic stereo correlation, it would be possible to have it digitized as a service. Production costs for digital terrain models and

---

[202] Yakimovsky, Y., "Extracting Depth Information From a Stereo Pair", Milwaukee Symposium on Automatic Control, pp. 311-316, 1974.

[203] Liebes, S. and Schwartz, A., "Viking 1975 Mars Lander Interactive Computerized Video Stereophotogrammetry", Journal of Geophysical Research, Vol. 82, No. 28, pp. 4421-4429, September 1977.

[204] Speakman, E. and Stanton, J., "Is the Stereoplanigraph Obsolete", American Institute of Aeronautics and Astronautics, 1974.

orthophotos (Hagan[205], Gockowski[206], and Foster[207]) should not exceed $25 - $50 per square mile when elevations are required on a fixed 30 meter grid.

Recommendation. Stereo analysis equipment consisting of a metric camera, surveying instruments (to obtain ground control) an analytical stereo plotter and software to interface to modeling system is recommended. The products of such a system would be specific object geometric models which can be used as generic models to form an environment.

DIGITAL IMAGE PROCESSING EQUIPMENT

The application of digital image processing equipment to interactive environmental data base development is relatively limited in that the tasks which are done best by current equipment have, for the most part, been done. The segmenting of a geographic area into areas labeled with predominant feature classifications is included in the digital land mass system (DLMS) (DMA[208]). The more sophisticated artificial intelligence type of applications are extremely limited in scope and are best applied to specific pattern or shape recognition tasks. However, there are some relatively simple application of digital image processing which can be utilized by a data base modeler. These include; the use of a digitizer to measure color of an object surface in a color photograph, the use of enhancement techniques to make imagery more comfortable to view or to emphasize classes of features, measurement of gray level variation or texture within an image region corresponding to an object surface.

Andrews[209] describes the digital image processing facility at the University of Southern California Image Processing Institute. Schrock[210] and Gambino[211] describe the facility at the U.S. Army Engineering Topographic Laboratory.

---

[205] Hagan, W., "Observations on USGS - State Cooperative Mapping", Photogrammetric Engineering and Remote Sensing, Vol. 45, No. 12, pp. 1617-1620, December 1979.

[206] Gockowski, J., "Mapping Cooperation Among Civilian Agencies", Photogrammetric Engineering and Remote Sensing, Vol. 45, No. 12, pp. 1629-1631. December 1979.

[207] Foster, H.; Bos, J.; and Richie, C., "A Remote Sensing System for a Nationwide Data Bank", in Proc. Machine Processing of Remotely Sensed Data Symposium, IEEE Catalog No. 77CH1218-7, MPRSD, pp. 160-171, June 1977.

[208] Defense Mapping Agency, "Product Specifications for Digital Landmass System (DLMS) Data Base, PS/ICD-E-F-G/100, July 1977.

[209] Andrews, H., "An Educational Digital Image Processing Facility", Computer, Vol. 10, No. 8, pp. 48-53, August 1977.

[210] Schrock, B., "Interactive Interpretation of Digital Imagery", SPIE, Proc. on Airborne Reconnaisance III, Vol. 137, pp. 188-194, March 1978.

[211] Gambino, L. and Schrock, B., "An Experimental Digital Interactive Facility", Computer, Vol. 10, No. 8, pp. 22-28, August 1977.

Faust[212] describes the pattern recognition facility at Rome Air Development Center. Wilson[213] describes the system at the Marshall Space Flight Center used for image enhancement and image restoration. Cunningham[214] describes the five major components of a system as; digitizer (microdensitometer or television), digital computer, computer to hard copy output, color CRT monitor, and custom interfaces. Rohrbacher[215] describes high-speed image processing with the STARAN parallel computer. Fanshier[216] describes the impact of currently available hardware on digital image processing systems. Wittig[217] describes techniques utilized for the production of 100 land use maps. He concludes that automatic segmentation is superior to manual digitizing only if the original photography is very clean to start with. He found that the major problems associated with manual digitizing were; inaccuracies, missing information, and digitization of the same point twice. Booth[218] describes all the system components in a digital image analysis system and their effects on end results. He states that an understanding of the long chain of transducers, signal conditioners, and processors which produced the image to analyze is essential to the analysis task. Reynolds[219] describes a technique for applying generic texture tiles to simulate real world texture.

---

[212] Faust, J.; Webb, H.; and Gerhardt, L., "The RADC Interactive Laboratory for Design of Pattern Recognition Systems and its Application", in Proc. of Conf. on Computer Graphics, Pattern Recognition, and Data Structure, IEEE Catalog No. 75CH0981-1C, pp. 258-272, May 1975.

[213] Wilson, R; Teuber, D.; Thomas, D.; and Watkins, J., "The MSFC Image Data Processing System", Computer, Vol. 10, No. 8, pp. 37-44, August 1977.

[214] Cunningham, R., "Update on Digital Image Processing", Electro-Optics System Design, pp. 34-41, July 1979.

[215] Rohrbacher, D. and Potter, J., "Image Processing With the Staran Parallel Computer", Computer, Vol. 10, No. 8, pp. 54-59, August 1977.

[216] Fanshier, D. and Andrews, H., "Impact of RAM Multiported Memories on Interactive Digital Image Processing Systems", SPIE, Vol. 199, pp. 35-41, August 1979.

[217] Wittig, G., "Interactive Manipulation of Land Use Data", in Proc. of International Conference on Interactive Techniques in Computer Aided Design", IEEE Catalog No. 78CH1289-8C, pp. 216-222, 1978.

[218] Booth, J. and Schroeder, J., "Design Consdierations for Digital Image Processing Systems", Computer, Vol. 10, No. 8, pp. 15-20, August 1977.

[219] Reynolds, R.; Dungan W.; and Sutty, G., "Depth Perception and Motion Cues via Textured Scenes", in Proc. AIAA Flight Simulation Technologies Conference, pp. 46-48.

Recommendation. Digital image processing equipment should be restricted to a television digitizer (3-color), a frame memory (3-color), and minimal hardware processing capability at the current time. As processing capability is driven to more generally applicable systems by other than CIG modeling requirements, continue to reevaluate system performance for future system improvements.

SECTION VI

SUMMARY AND CONCLUSIONS

SCENE DETAIL REQUIREMENTS

This report reviewed an extensive body of literature describing visual capabilities and visual task performance in an effort to quantify the fidelity of a visual simulation to the real world. The required fidelity is highly task dependent and there is no general rule which will apply to all training situations. A recommendation is made to construct models which are faithful to the real world only to the degree necessary to identify the objects which are relevant to the visual tasks to be trained. In practice this could be accomplished using photographs in which images of objects are resolved only to an identification level as guides to the modeler.

DATA ACQUISITION AND REDUCTION

The generation of environment models from imagery is a difficult task even when automated techniques are used. The conversion of existing models to the desired form through the use of transformation software is the preferred approach if an existing model is available. The Computer Systems Laboratory at NAVTRAEQUIPCEN has been and will continue to be developing this approach to automatic data base generation.

In the case of real world environments which have not been reduced to models the techniques of *stereophotogrammetry and digital image processing* offer potential improvements to the data base generation process. The quantification of the improvement in efficiency can be determined by comparing the actual costs of manual modeling to a modeling procedure incorporating these techniques when modeling the same environment from the real world to the same degree of fidelity.

The use of artificial intelligence techniques for converting image information into a semantic model which then may be converted into a CIG environment model is a potential future solution to automating the data base generation process. However, the current state-of-the-art is not sufficiently developed to apply these techniques to complex visual environments.

REFERENCES

Abdel-Aziz, Y. and Karara, H., "Photogrammetric Potentials of Non-metric cameras" University of Illinois at Urbana, PB-231-254, March 1974.

Abshier, J., "TA3/PA and AS-11B-1 Improvement Study", AD904906L, September 1972.

Agin, G. et al., "Interactive Aids for Cartography and Photo-Interpretation", ADA056355, June 1978.

Agin, G. J., "Hierarchical Representation of Three-Dimensional Objects Using Semantic Models" in Proceedings of Workshop on the Representation of Three-Dimensional Objects, Bajcsy, R. (ED.) The Department of Computer and Information Science, University of Pennsylvania, May 1979.

Agrawala, A., "Machine Recognition of Patterns", IEEE Press, John Wiley and Sons, Inc., New York, 1976.

Ali, M. et al., "Color-Based Computer Analysis of Aerial Photographs", Computer Graphics and Image Processing, Vol. 9, pp. 282-293, 1979.

Allam, M., "DTM's Application in Topographic Mapping", in Proc. of Digital Terrain Models (DTM) Symposium, American Society of Photogrammetry, May 1978.

Andrews, H. and Hunt, B., "Digital Image Restoration", Prentice-Hall Inc., New Jersey, 1977.

Andrews. H., "An Educational Digital Image Processing Facility", Computer, Vol. 10, No. 8, pp. 48-53, August 1977.

Appel, A., "Modeling in Three Dimensions", IBM Systems Journal, Nos. 3 and 4, pp. 310-321, 1968.

Ayeni, O., "Considerations for Automated Digital Terrain Models With Applications in Differential Photo Mapping", Ph.D. Dissertation, The Ohio State University, 1976, (Avail. NTIS).

Bajcsy, R. et al., "What Can One See on the Earth From Different Altitudes" in Proceedings IEEE Computer Society Conference on Pattern Recognition and Image Processing, pp. 108-111, June 1977.

Basinger, J. and Ingle, S., "Data Base Requirements for Full Mission Simulation" in Proceedings of the 1977 Image Conference, Air Force, Human Resources Laboratory, Flying Training Division, Williams AFB, Arizona, pp. 25-33, May 1977.

Bendix Research Laboratories, "Photogrammetry at Bendix", Bendix Center, Southfield, Michigan, 48076.

Bergeron, R., "Standards for Interactive Computer Graphics Software" in Proc. of Workshop on Picture Data Description and Management, IEEE Computer Society, pp. 126-129, April 1977.

Biberman, L. (Editor), "Perception of Displayed Information", Plenum Press, New York, 1973.

Black, S., "Digital Processing of 3-D Data to Generate Interactive Real-Time Dynamic Pictures" in Three Dimensional Imaging, SPIE, Vol. 120, 1977.

Blinn, J. and Newell, M., "Texture and Reflection in Computer Generated Images", Communications of the ACM, Vol. 19, No. 10, pp. 542-547, October 1976.

Blinn, J., "Computer Display of Curved Surfaces", Ph.D. Thesis, University of Utah, December 1978.

Blinn, J., "Geometric Representations in Computer Graphics" in Proceedings of Workshop on the Representation of Three Dimensional Objects, Bajcsy, R. (ED.), The Department of Computer and Information Science, University of Pennsylvania, May 1979.

Booth, J. and Schroeder, J., "Design Considerations for Digital Image Processing Systems", Computer, Vol. 10, No. 8, pp. 15-20, August 1977.

Booth, J. and Farrell, R., "Overview of Human Engineering Considerations for Electro-Optical Displays", SPIE, Vol. 199, pp. 78-108, August 1979.

Braid, I., "The Synthesis of Solids Bounded by Many Faces", Communications of ACM, Vol. 18, No. 4, pp. 209-216, April 1975.

Brewer, J. and Anderson, D., "Visual Interaction With Overhauser Curves and Surfaces", Computer Graphics, Vol. 11, No. 2, pp. 132-137, Summer 1977.

Brooks, R. A. et al., "Progress Report on a Model Based Vision System" in Proceedings of Workshop on the Representation of Three Dimensional Objects, Bajcsy, R. (ED.), The Department of Computer and Information Science, University of Pennsylvania, May 1979.

Brown, C.; Requicha, A.; and Voelcker, H., "Geometric Modelling Systems for Mechanical Designs and Manufacturing", prepared for presentation at ACM 78, December 4-6 1978.

Brown, C. M., "Some Issues and Answers in Geometric Modelling" in Proceedings of Workshop on the Representation of Three-Dimensional Objects, Bajcsy, R. (ED.), The Department of Computer and Information Science, University of Pennsylvania, May 1979.

Bunker, W., "Computer Image Generation Imagery Improvement: Circles, Contours, and Texture", Technical Report AFHRL-TR-77-66, Advanced Systems Division, Air Force Human Resources Laboratory, Wright-Patterson Air Force Base, Ohio, September 1977.

Bunker, W., "Training Effectiveness Versus Simulation Realism", SPIE, Vol. 162, Visual Simulation and Image Realism, pp. 76-82, August 1978.

Bunker, M and Ingalls, M., "Circles, Texture, Etc.; Alternate Approaches to CIG Scene Detail", in Proc. AIAA Flight Simulation Technologies Conference, pp. 49-58, September 1978.

Bunker, W., "CIG Translucent Face Simulation Provides Multiple Benefits", Proc. of 1st Interservice/Industry Training Equipment Conference, pp. 229-238, November 1979.

Carel, W.; Herman, J.; and Olzak, L., "Design Criteria for Imaging Sensor Displays", ADA055411, May 1978.

Carlbom, I and Paciorek, J., "Planar Geometric Projections and Viewing Transformations", Computing Surveys, Vol. 10, No. 4, pp. 465-502, December 1978.

Carlson, E., "Graphics Terminal Requirements for the 1970's" in Tutorial on Computer Graphics, IEEE Catalog No. EHO-147-9, pp. 126-134, 1979.

Casasent, D. ED., "Optical Data Processing Applications", Springer-Verlag, New York, 1978.

Catmull, E., "A Subdivision Algorithm for Computer Display of Curved Surfaces", ADA 004968, December 1974.

Catmull, E., "Computer Display of Curved Surfaces", in Proc. of Conf. on Computer Graphics, Pattern Recognition, and Data Structure, IEEE Catalog No. 75CH0981-1C, pp. 11-17, May 1975.

Chase, W., "Effect of Color on Pilot Performance and Transfer Functions Using a Full-Spectrum, Calligraphic, Color Display System" in Proceedings of AIAA Vision Simulation and Motion Conference, April 1976.

Christ, R., "Four Years of Color Research for Visual Displays", in Proc. of Human Factors Society - 21st Annual Meeting, pp. 319-321, October 1977.

Ciavarelli, A.; Wachter, L.; and Lee, W., "Terrain Classification Study", AD B005535, May 1975.

Clark, J., "Designing Surfaces in 3-D", Comm. of ACM, Vol. 19, No. 8, pp. 454-460, August 1976.

Clark, J., "Hierarchical Geometric Models for Visible Surface Algorithms", in Tutorial on Computer Graphics, IEEE Catalog No. EHO-147-9, pp. 222-229, 1979.

Cornsweet, T., "Visual Perception", Academic Press, New York, 1970.

Craig, G., "Vehicle Detection on Television; A Laboratory Experiment", AD919898, April 1974.

Crow, F., "Shaded Computer Graphics in the Entertainment Industry", in Tutorial on Computer Graphics, IEEE Catalog No. EHO-147-9, 1979.

Csuri, C., "Computer Graphics and Art", in Tutorial on Computer Graphics, IEEE Catalog No. EHO-147-9, pp. 421-433, 1979.

Cunningham, R., "Update on Digital Image Processing", Electro-Optics System Design, pp. 34-41, July 1979.

Davis, L., "A Survey of Edge Detection Techniques", Computer Graphics and Image Processing, Vol. 4, pp. 248-270, 1975.

Della Vigna, P. and Luccio, F., "Some Aspects of the Recognition of Convex Polyhedra From Two Plane Projections", Information Sciences, Vol. 2, pp. 159-178, 1970.

Defense Mapping Agency, "Product Specifications for Digital Landmass System (DLMS) Data Base, PS/ICD-E-F-G/100, July 1977.

Defense Mapping Agency Aerospace Center, "Test and Evaluation of USAF Project 1183 Digital Data Bases", DMAAC TR 79-1, February 1979.

Duda, R. O. et al, "Use of the Hough Transformation to Detect Lines and Curves in Pictures", Communications of the Association for Computing Machines, Vol. 15, pp. 11-15, January 1972.

Duda, R. and Hart, P., "Pattern Classification and Scene Analysis", John Wiley and Sons, New York, 1973.

Duda, R. et al., "Use of Range and Reflectance Data to Find Planar Surface Regions", IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. PAMI-1, No. 3, July 1979.

Dungan, W., "A Terrain and Cloud Computer Image Generation Model", Computer Graphics, Vol. 13, No. 2, pp. 143-150, August 1979.

Dutton, G., "An Extensible Approach to Imagery of Gridded Data", Computer Graphics, Vol. II, No. 2, pp. 159-169, Summer 1977.

Edson, D. and Lee, G., "Ways of Structuring Data Within a Digital Cartographic Data Base", Computer Graphics, Vol. II, No. 2, Summer 1977.

Erickson, R. and Hemingway, J., "Image Identification on Television", Report NWC-TP-5025 Naval Weapons Center, China Lake, California, AD876332.

Faintich, M.; Sigler, G.; and Fahy, D., "Digital Image Display and Simulation From Digital Terrain Data Bases", in Proc. of Digital Terrain Models (DTM) Symposium, American Society of Photogrammetry, pp. 610-616, May 1978.

Fanshier, D. and Andrews, H., "Impact of RAM Multiported Memories on Interactive Digital Image Processing Systems", SPIE, Vol. 199, pp. 35-41, August 1979.

Farrell, R. and Booth, J., "Design Handbook for Imagery Interpretation Equipment", Boeing Aerospace Company, Seattle, Washington, December 1975.

Faust, J.; Webb, H.; and Gerhardt, L., "The RADC Interactive Laboratory for Design of Pattern Recognition Systems and its Application", in Proc. of Conf. on Computer Graphics, Pattern Recognition, and Data Structure, IEEE Catalog No. 75CH0981-1C, pp. 258-272, May 1975.

Forrest, A., "Recent Trends in Computer Aided Geometric Design", in Proc. of International Conference on Interactive Techniques in Computer Aided Design, IEEE Catalog No. 78CH1289-8C, pp. 141-146, 1978.

Foster, H.; Bos, J.; and Richie, C., "A Remote Sensing System for a Nationwide Data Bank", in Proc. Machine Processing of Remotely Sensed Data Symposium, IEEE Catalog No. 77CH1218-7, MPRSD, pp. 160-171, June 1977.

Fowler, R. and Little, J., "Automatic Extraction of Irregular Network Digital Terrain Models", Computer Graphics, Vol. 13, No. 2, pp. 199-207, August 1979.

Fuchs, H., "The Automatic Sensing and Analysis of Three-Dimensional Surface Points From Visual Scenes", Ph.D. Dissertation available from University Microfilms, Ann Arbor, Michigan, 1975.

Fuchs, H.; Kedem, Z.; and Uselton, S., "Optimal Surface Reconstruction From Planar Contours", Communications of the ACM, Vol. 20, No. 10, pp. 693-702, October 1977.

Gambino, L. and Schrock, B., "An Experimental Digital Interactive Facility", Computer, Vol. 10, No. 8, pp. 22-28, August 1977.

Gardner, G., "Computer Image Generation System With Efficient Image Storage", in Optical Information Storage, SPIE, Vol. 177, pp. 10-12, 1979.

Gardner, G., "Computer-Generated Texturing to Model Real-World Features", in Proc. of 1st Interservice/Industry Training Equipment Conference, pp. 239-246, November 1979.

Gaven, J.; Tavitian, J.; and Harabedian, A., "The Informative Value of Sampled Images as a Function of the Number of Gray Levels Used in Encoding the Images", Photographic Science and Engineering, Vol. 14, pp. 168, 1970.

Gibson, J., "The Perception of the Visual World", Houghton-Mifflin Company, Boston, 1950.

Gockowski, J., "Mapping Cooperation Among Civilian Agencies", Photogrammetric Engineering and Remote Sensing, Vol. 45, No. 12, pp. 1629-1631.

Gonzalez, R. and Wintz, P., "Digital Image Processing", Addison-Wesley Publishing Co., Reading, Massachusetts, 1977.

Granda, T., "A Comparison Between a Standard Map and a Reduced Detail Map Within a Simulated Tactical Operations System (SIMTOS)", Army Research Institute, ADA028752.

Greenberg, D., "An Interdisciplinary Laborary for Graphics Research and Applications", Computer Graphics, Vol. 11, No. 2, pp. 90-97, Summer 1977.

"Graphic Standards Planning Committee Status Report", Computer Graphics, Vol. 13, No. 3, August 1979.

Guzman, A., "Computer Recognition of Three-Dimensional Objects in a Visual Scene", Ph.D. Thesis, Massachusetts Institute of Technology, December 1968.

Hackathron, R., "ANIMA II: A 3-D Color Animation System", Computer Graphics, Vol. II, No. 2, pp. 54-64, Summer 1977.

Hagan, W., "Observations on USGS - State Cooperative Mapping", Photogrammetric Engineering and Remote Sensing, Vol. 45, No. 12, pp. 1617-1620, December 1979.

Hall, E.; Hwang, J.; Lee, C.; and Hwang, M., "Measuring Scene Content From Aerial Images", SPIE, Vol. 186, pp. 215-223, May 1979.

Hamilton, H., "Feasibility Study for Simulation of an Airport Tower Control Environment", ADA051174, February 1978.

Haralick, R.; Shanmugam, K.; and Dinstein, I., "Textural Features For Image Classification", IEEE , Trans. on Syst., Man, and Cybernetics, Vol. SMC-3, pp. 610-621, November 1973.

Helava, U., "Instruments and Methods for Digital Terrain Model Data Collection", in Proc. of the Digital Terrain Models (DTM) Symposium, American Society of Photogrammetry, pp. 61-71, May 1978.

Hemami, H.; Weimer, F.; and Advani, J., "Identification of Three-Dimensional Objects by Sequential Image Matching", IEEE, Proc. of Conference on Computer Graphics, Pattern Recognition, and Data Structure, Catalog No. 75CHO 981-1C, pp. 273-278.

Henderson, R.; Miller, W.; and Grosch, C., "Automatic Stereo Reconstruction of Man-Made Targets", SPIE, Vol. 186, pp. 240-248.

Herman, G. T., "Representation of 3-D Surfaces by a Large Number of Simple Surface Elements", in Proceedings of Workshop and Representation of Three-Dimensional Objects, Department of Computer and Information Sciences, University of Pennsylvania, May 1979.

Hoffmann, H. and Buell, R., "Results of Field Experiments Concerning Visibility of Objects", ADB017717 (Limited Distribution), May 1977.

Hoog, T.; Dahlberg, R.; and Robinson, R., "Project 1183: An Evaluation of Digital Radar Landmass Simulation", in Proceedings of NTEC/Industry Conference NAVTRAEQUIPCEN, IH-240, pp. 54-79, November 1974.

Hoog, T. and Stengel, J., "Computer Image Generation Using the Defense Mapping Agency Digital Data Base", in Proc. of the 1977 Image Conference at Williams Air Force Base, pp. 203-218, May 1977.

Hoog, T., "Correlated Data Bases for the Present and Future", in Proc. AIAA Flight Simulation Technologies Conference, pp. 73-78, September 1978.

Hosaka, M. and Kimura, F., "Synthesis Methods and Curves and Surfaces in Interactive CAD", in Proc. of International Conference on Interactive Techniques in Computer Aided Design, IEEE Catalog No. 78 CH1289-8C, pp. 151-155, 1978.

Hubble, L. and Reader, C., "State of the Art in Image Display Systems", SPIE, Vol. 199, pp. 2-8, August 1979.

Hueckel, M., "An Operator Which Locates Edges in Digitized Pictures", Journal of the Association of Computing Machines, Vol. 18, pp. 113-125, January 1971.

Hunt, E., "Artificial Intelligence", Academic Press, New York, 1975.

Hunt, R., "The Reproduction of Colour", Fountain Press, England, 1975.

Hunt, B. and Ryan, T., "Prediction of Correlation Errors in Parallax Computation From Digital Stereo Images", in Applications of Digital Image Processing, SPIE, Vol. 149, pp. 222-231, August 1978.

Hwang, J.; Lee, C.; and Hall, E., "Segmentation of Solid Objects Using Global and Local Edge Coincidence", in Proceedings of IEEE Computer Society's Conference on Pattern Recognition and Image Processing, pp. 114-121, August 1979.

Jackson, P., "Introduction to Artificial Intelligence", Petrocelli/Charter, New York, 1974.

Jaksic, Z., "Analytical Instruments in Close-Range Photogrammetry", in Proc. of Symposium on Close-Range Photogrammetric Systems, American Society of Photogrammetry, pp. 538-555, July 1975.

Jancaitis, J. and Moore, W., "Near Real-Time Application of Digital Terrain Data in a Mincomputer Environment", AD-A054008, April 1978.

Jayroe, R. and Underwood, D., "Vector Statistics of LANDSAT Imagery", NASA Tech Memo, TM 78149, December 1977.

Karara, H., "Industrial Photogrammetry", in Proc. of Symposium on Close-Range Photogrammetric Systems, American Society of Photogrammetry, pp. 97-141, July 1975.

Kasvand, T., "Some Observations on Linguistics for Scene Analysis", in Proceedings of IEEE Computer Society Conference and Computer Graphics, Pattern Recognition, and Data Structure, pp. 118-124, May 1975.

Keating, T., "Analytical Photogrammetry From Digitized Image Densities", Ph.D. Dissertation, University of Wisconsin, 1975, (Avail. NTIS).

Keating, T. and Boston, D., "Digital Orthophoto Production Using Scanning Microdensitometers", Photogrammetric Engineering and Remote Sensing, Vol. 45, No. 6, pp. 735-740, June 1979.

Kelly, R.; McConnell, P.; and Mildenberger, S., "The Gestalt Photomapping System", Photogrammetric Engineering and Remote Sensing, Vol. 43, No. 11, pp. 1407-1417, November 1977.

Key, D.; Odneal, B.; and Sinacori, J., "Mission Environment Simulation for Army Rotorcraft Development - Requirements and Capabilities", in AGARD Conference, Proc. #249, (ADA063850), pp. 4-1, 4-17, April 1978.

Konecny, G., "Methods and Possibilities for Digital Differential Rectification", Photogrammetric Engineering and Remote Sensing, Vol. 45, No. 6, pp. 727-734, June 1979.

Kotas, J. and Booker J., "The AWAVS Data Base Facility - A Comprehensive Preparation Package", in Proc. of 11th NTEC/Industry Conference, pp. 49-62, November 1978.

Kraft, C.; Elworth, C.; Anderson, C.; and Allsopp, W., "Pilot Acceptance and Performance Evaluation of Visual Simulation", in Proc. of 9th NTEC/ Industry Conference, pp. 235-249, November 1976.

Kraft, C. and Shaffer, L., "Visual Criteria for Out of the Cockpit Visual Scenes", in AGARD Conference Proceedings No. 249, ADA063830, pp. 3-1, 3-18, April 1978.

Kraus, K.; Otepka, G.; Loitsch, J.; and Haitzmann, H., "Digitally Controlled Production of Orthophotos and Stereo-Orthophotos", Photogrammetric Engineering and Remote Sensing, Vol. 45, No. 10, pp. 1353-1362, October 1979.

Lacina, W. and Nicholson, W., "Passive Determination of Three Dimensional Form From Dynamic Imagery", SPIE, Vol. 186, pp. 178-189, May 1979.

Latta, J., "New Developments in Digital Image Processing Displays", SPIE, Vol. 164, pp. 164-171, 1977.

LeGrand, Y., "Form and Space Vision", Indiana University Press, Bloomington, 1967.

Leighty, R., "Concepts for Automated Pattern Recognition Research With Hybrid Optical/Digital Systems", in Data Extraction and Classification From Film, SPIE, Vol. 117, pp. 132-139.

Levin, J., "A Parametric Algorithm for Drawing Pictures of Solid Objects Composed of Quadric Surfaces", Communications of the ACM, Vol. 19, No. 10, pp. 555-563, October 1976.

Liebes, S. and Schwartz, A., "Viking 1975 Mars Lander Interactive Computerized Video Stereophotogrammetry", Journal of Geophysical Research, Vol. 82, No. 28, pp. 4421-4429, September 1977.

Lintz, J. and Simonett, D. (Editors), "Remote Sensing of Environment", Addison-Wesley, Reading, Massachusetts, 1976.

MacAdam, D., "Visual Sensitivities to Color Differences in Daylight", Journal of the Optical Society of America, Vol. 32, No. 5, pp. 247-274, May 1942.

Mahl, R., "Visible Surface Algorithms for Quadric Patches", AD-762017, December 1970.

Marconi Radar Systems Limited, Product Brochure, "A Picture Generator for Flight Simulators".

Mark, D., "Concepts of Data Structure for Digital Terrain Models", in Proc. of Digital Terrain Models (DTM) Symposium, American Society of Photogrammetry, May 1978.

Martin, S., "Color Image Maps From Black and White Photographs", Photogrammetric Engineering and Remote Sensing, Vol. 46, No. 2, pp. 193-200, February 1980.

McGrath, J., "The Use of Wide-Angle Cinematic Simulators in Pilot Training", Technical Report NAVTRAEQUIPCEN 70-C-0306-1, March 1973.

McKee, J. and Aggarwal, J., "Computer Recognition of Partial Views of Three Dimensional Curved Objects", in Proc. of Conference on Pattern Recognition, IEEE Catalog No. 76 CH1140-3C, pp. 499-503, November 1976.

McKeown, D. et al., "A Hierarchical Symbolic Representation for an Image Data Base", in Proceedings of IEEE Computer Society Workshop on Picture Data Description and Management, pp. 40-44, April 1977.

Mezrich, J.; Carlson, C.; and Cohen, R., "Image Descriptors for Display", Office of Naval Research Report ONR-CR213-120-3, February 1977.

Monroe, E., "Environmental Data Base Development Process for the ASUPT CIG System", Air Force Human Resources Laboratory, Technical Report AFHRL-TR-75-24, August 1975.

Monroe, E., "Air to Surface Full Mission Simulation by the ASUPT System", in Proc. of 9th NTEC/Industry Conference, pp. 41-48, November 1976.

Morland, D., "System Description - Aviation Wide-Angle Visual System (AWAVS) Computer Image Generator (CIG) Visual System", Technical Report NAVTRAEQUIPCEN 76-C-0048-1, Naval Training Equipment Center, Orlando, Florida, February 1979.

Munchmeyer, F. and Lau, G., "On the Iterative Design of Smooth Patched Surfaces", in Proc. of International Conference on Interactive Techniques in Computer Aided Design, IEEE Catalog No. 78CH1289-8C, pp. 147-150, 1978.

Nagao, M. et al, "Agricultural Land Use Classification of Aerial Photographs by Histogram Similarity Method", Proceedings of IEEE Computer Society Conference on Pattern Recognition, pp. 669-672, November 1976.

Neff, J. and Flannery, D., "Air Force Research in Optical Processing", in Optical Signal and Image Processing, SPIE, Vol. 118, pp. 2-5, 1977.

Nesterikhin, Y.; Stroke, G.; and Kock, W., (Eds.), "Optical Information Processing", Plenum Press, New York, 1976.

Nevatia, R., "Depth Measurement by Motion Stereo", Computer Graphics and Image Processing, pp. 203-214, May 1976.

Nevatia, R., "Locating Object Boundaries in Textured Environments", IEEE Trans on Computers, Vol. C-25, No. 11, pp. 1170-1175, November 1976.

Nevatia, R. and Binford, T., "Description and Recognition of Curved Objects", Artificial Intelligence, Vol. 8, pp. 77-98.

Nevatia, R., "A Color Edge Detector and its Use in Scene Segmentation", IEEE Trans. on Systems, Man, and Cybernetics, Vol. SMC-7, No. 11, pp. 518-524, November 1977.

Newman, W. and Sproull, R., "Principles of Interactive Computer Graphics", 2nd Edition, McGraw-Hill Book Company, 1979.

O'Connor, F; Shinn, J.; and Bunker, W., "Prospects, Problems, and Performance: A Case Study of the First Pilot Trainer Using CGI Visuals", in Proc. of Sixth NTEC/Industry Conference, pp. 55-83, November 1973.

Ohlson, M., "System Design Considerations for Graphics Input Devices", in Tutorial on Computer Graphics, IEEE Catalog No. EHO 147-9, pp. 282-290, 1979.

Optical Society of America, "The Science of Color", Optical Society of America, Washington, D.C., 1963.

Ozkaptan, H., "Critical Visual Requirements for Nap of the Earth (NOE) Flight Research", in Proc. 8th NTEC/Industry Conference, pp. 53-65, November 1975.

Panton, D., "Digital Orthophoto Study", ADA020066, December 1975.

Panton, D., "A Flexible Approach to Digital Stereo Mapping", in Proc. of Digital Terrain Models (DTM) Symposium, American Society of Photogrammetry, pp. 32-60, May 1978.

Parent, R., "A System for Sculpting 3-D Data", Computer Graphics, Vol. II, No. 2, pp. 138-147.

Phillips, R., "Computer Graphics in Urban and Environmental Systems", in Tutorial on Computer Graphics, IEEE Catalog No. EHO-147-9, pp. 405-420, 1979.

Potmesil, M., "Generation of 3-D Surface Descriptions From Images of Pattern-Illuminated Objects", in Proceedings of IEEE Computer Society Conference on Pattern Recognition and Image Processing, pp. 553-559, August 1979.

Pratt, W., "Digital Image Processing", John Wiley and Sons, New York, 1978.

Requicha, A. and Voelcker, H., "Constructive Solid Geometry", U.S. Dept. of Commerce, PB281613, November 1977.

Reynolds, R.; Dungan W.; and Sutty, G., "Depth Perception and Motion Cues via Textured Scenes", in Proc. AIAA Flight Simulation Technologies Conference, pp. 46-48.

Richards, W., "Experiments in Texture Perception", ADA059630, January 1978.

Richie, M., "Object, Illusion, and Frame of Reference as Design Criteria for Computer-Generated Displays", SPIE, Vol. 162, Visual Simulation and Image Realism, pp. 8-10, August 1978.

Rivers, H. and VanArsdall, R., "Simulator Comparative Evaluation", in Proc. of 10th NTEC/Industry Conference, pp. 37-42, November 1977.

Rivers, H. A., "Simulator Comparative Evaluation", ADB023450 (Limited Distribution).

Roberts, L., "Machine Perception of Three-Dimensional Solids", in Optical and Electro-Optical Information Processing, J. T. Tippett et al., EDS., MIT Press, Cambridge, Massachusetts, pp. 159-197, 1965.

Roese, J., "Stereoscope Computer Graphics for Simulation and Modelling", Computer Graphics, Vol. 13, No. 2, pp. 41-47.

Rohrbacher, D. and Ptter, J., "Image Processing With the Staran Parallel Computer", Computer, Vol. 10, No. 8, pp. 54-59, August 1977.

Rosenfeld, A., "Extraction of Topological Information From Digital Images", ADA042125, June 1977.

Sagan, C., "The Dragons of Eden", Ballantine Books, New York, 1977.

Salmen, L.; Gropper, J.; Hamill, J.; and Reed, C., "Comparison of Selected Operational Capabilities of Fifty-Four Geographic Information Systems", U.S. Department of Commerce, PB-286977, September 1977.

Sanders, M.; Simmons, R.; Hofmann, M.; and DeBonis, J., "Visual Workload of the Co-Pilot/Navigator During Terrain Flight", Proc. of the Human Factors Society 21st Annual Meeting, pp. 262-266, October 1977.

Scanlan, L., "Target Acquisition in Realistic Terrain", in Proc. of the Human Factors Society - 21st Annual Meeting, pp. 249-253, October 1977.

Schachter, B., "Computer Generation of Full Colored Textured Terrain Images", in Proc of 1st Interservice/Industry Training Equipment Conference, pp. 367-374, November 1979.

Schnitzer, A., "A Data Base Generation System for Digital Image Generation", in Proc. of 9th NTEC/Industry Conference, pp. 103-113, November 1976.

Schrock, B., "Interactive Interpretation of Digital Imagery", SPIE, Proc. on Airborne Reconnaisance III, Vol. 137, pp. 188-194, March 1978.

Schumacher, R. and Rougelot, R., "Image Quality: A Comparison of Night/Dusk and Day/Night CGI Systems", in Proceedings of the 1977 Image Conference held at Williams AFB, Arizona, 17-18 May 1977, pp. 243-255.

Scott, F.; Hollanda, P.; and Harabedian, A., "The Informative Value of Sampled Images as a Function of the Number of Scans Per Scene Object", Photographic Science and Engineering, Vol. 14, No. 1, pp. 21-27, January 1970.

Shapira, R. and Freeman, H., "Computer Description of Bodies Bounded by Quadric Surfaces From a Set of Imperfect Projections", IEEE Trans. on Computers, Vol. C-27, No. 9, pp. 841-854, September 1978.

Shneiderman, B., "Human Factors Experiments in Designing Interactive Systems", Computer, pp. 9-19, December 1979.

Soroka, B. et al., "A Program for Describing Complex Three-Dimensional Objects Using Generalized Cylinders as Primitives", in Proceedings of IEEE Computer Society Conference on Pattern Recognition and Image Processing, pp. 331-339, June 1978.

Speakman, E. and Stanton, J., "Is the Stereoplanigraph Obsolete", American Institute of Aeronautics and Astronautics, 1974.

Stark, E.; Bennett, W.; and Borst, G., "Designing DIG Images for Systematic Instruction", in Proc. of 10th NTEC/Industry Conference, pp. 147-155, November 1977.

Sties, M. et al., "Organization of Object Data for an Image Information System", in Proceedings of IEEE Computer Society Conference on Pattern Recognition, pp. 863-869, November 1976.

Strat, T., "Shaded Perspective Images of Terrain", ADA055070, March 1978.

Sutherland, I., "Three-Dimensional Data Input by Tablet", in Tutorial on Computer Graphics, IEEE Catalog No. EHO-147-9, pp. 266-274, 1979.

Sutherland, I.; Sproull, R.; and Schumacker, R., "Characterization of Ten Hidden-Surface Algorithms", Computing Surveys, Vol. 6, No. 1, pp. 1-55, March 1974.

Swallow, R., "Computrol Computer Generated Day/Dusk/Night Image Display", in Proceedings of 11th NTEC/Industry Conference, pp. 321-331, November 1978.

Tamura, H., "Textural Features Corresponding to Visual Perception", IEEE Transactions on Systems, Man, and Cybernetics, Vol. SMC-8, No. 6, pp. 460-473, June 1978.

Thomason, M., "Applications of Probalistic Information Theory to Relational Data Bases", SPIE, Vol. 186, pp. 224-229.

Thompson, M. (Editor), "Manual of Photogrammetry", American Society of Photogrammetry, Falls Church, VA, 1966.

Thorpe, J.; Varney, N.; McFadden, R.; LeMaster, W.; and Short, L., "Training Effectiveness of Three Types of Visual Systems For KC-135 Flight Simulators", Air Force Human Resources Laboratory, Flying Training Division Report AFHRL-TR-78-16, June 1978.

Tou, J. etal., "Picture Understanding by Machine Via Textural Feature Extraction", in Proceedings of IEEE Computer Society Conference on Pattern Recognition and Image Processing, pp. 392-399, June 1977.

Towles, R., "An Experimental Approach to Generation of Digital Landmass Data Base Culture/Planimetric Files Using LANDSAT Imagery and Multispectral Image Analysis Techniques", Proc. American Society of Photogrammetry, Fall Technical Meeting, October 1977.

Trimble, J., "Navy Optical Processing Programs for Systems Applications - An Historical Overview", in Optical Signal and Image Processing, SPIE, Vol. 118, pp. 96-99, 1977.

Unruh, J.; Alspaugh, D.; and Mikhail, E., "Image Simulation From Digital Data", in Proceedings of American Congree on Surveying and Mapping, 1977.

VanWijk, M., "Geometrical Quality of Stereo-Orthophotos Produced From Automatic Image Correlation Data", Photogrammetric Engineering and Remote Sensing, Vol. 45, No. 10, pp. 1363-1369, October 1979.

Vatz, B., "The Moving Technology", SPIE, Vol. 118, Optical Signal and Image Processing, pp. 142-143, 1977.

Vickers, D., "Sorcerer's Apprentices Head-Mounted Display and Wand", in Proc. of Symposium on Visually Coupled Systems: Development and Application, Brooks AFB, Aerospace Medical Division (Limited Distribution), pp. 522-540, November 1973.

Voelcker, H. and Requicha, A., "Geometric Modeling of Mechanical Parts and Processes", Computer, pp. 48-57, December 1977.

Wagner, D., "Target Detection With Color Versus Black and White Television", Report TP5731, Naval Weapons Center, China Lake, CA, April 1975.

Watkins, G., "A Real-Time Visible Surface Algorithm", AD-762004, June 1970.

Wekwerth, M., "The Lufthansa Day/Night Computer Generated Visual System", in AGARD Conference Proc. No. 249 (ADA063850), pp. 12-1, 12-6, April 1978.

Welch, B., "Recent Advances in Television Visual Systems", in AGARD Conference Proceedings #249, ADA063850, pp. 13-1, 13-7, April 1978.

Weszka, J.; Dyer, C.; and Rosenfeld, A., "A Comparative Study of Texture Measures for Terrain Classification", IEEE Trans on Systems, Man, and Cybernetics, Vol. SMC-6, No. 4, pp. 269-285, April 1976.

Wilson, R.; Teuber, D.; Thomas, D.; and Watkins, J., "The MSFC Image Data Processing System", Computer, Vol. 10, No. 8, pp. 37-44, August 1977.

Winston, P. (Editor), "The Psychology of Computer Vision", McGraw-Hill Book Company, New York, 1975.

Wittig, G., "Interactive Manipulation of Land Use Data", in Proc. of International Conference on Interactive Techniques in Computer Aided Design", IEEE Catalog No. 78CH1289-8C, pp. 216-222, 1978.

Wolf, P., "Elements of Photogrammetry", McGraw-Hill, New York, 1974.

Wood, M., "The Fidelity Issue in Visual Simulation", in Proc. of the 1977 Image Conference, Williams AFB, pp. 291-295, May 1977.

Woomer, C. and Williams, R., "Environmental Requirements for Simulated Helicopter/VTOL Operations From Small Ships and Carriers", in AGARD Conf. Proc. No. 249, Piloted Aircraft Environment Simulation Technologies, ADA063850, October 1978.

Wu, S.; Abel, J.; and Greenberg, D., "An Interactive Computer Graphics Approach to Surface Representation", Communications of ACM, Vol. 20, No. 10, pp. 703-712, October 1977.

Yakimovsky, Y., "Extracting Depth Information From a Stereo Pair", Milwaukee Symposium on Automatic Control, pp. 311-316, 1974.

Yan, J., "Real-Time Generation and Smooth Shading of Quadric Surfaces", in Proc. of 1st Interservice Industry Training Equipment Conference, pp. 247-260, November 1979.

Zucker, S. and Hummel, R., "An Optimal Three-Dimensional Edge Extractor", in Proceedings of IEEE Computer Society's Conference on Pattern Recognition and Image Processing, pp. 162-168, August 1979.

[illegible]

[illegible]
Cameron Station
Alexandria, VA 22314

Dr. [illegible]
[illegible]
U.S. Army Aviation R&D Command
Ames Research Center
Moffett Field, CA 94035

Mr. Ron Pierce
Visual Requirements
Defense Mapping Agency [illegible]
St. Louis, MO 63118

Dr. James Bynum
Army Research Institute
Ft. Rucker Field Unit
Ft. Rucker, AL 36362

Mr. [illegible]
Intelligence and Reconnaissance Division
Image Systems Branch
Rome Air Development Center
Griffiss AFB
Rome, NY

Mr. Tom [illegible]
Aeronautical Systems Division
Simulation Systems Program Office
Wright-Patterson AFB
Dayton, OH [illegible]

Mr. [illegible]
[illegible]
[illegible]
[illegible]
[illegible]

[illegible]

DATE
FILMED

2-8